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Decision support system for countermeasures in cruise ship flooding case

Thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Technology.

Espoo 24.7.2018
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Abstract

Several decision support systems have been developed during the last about ten years to assists crews of both naval and passenger ships in the decision making process during a flooding incident. NAPA Emergency Computer is a decision support system developed by Napa Ltd. for passenger ships to monitor the vulnerability of the ship and conduct a flooding prediction and a survivability assessment if ingress water is detected by the ship's flooding sensors, and to which this thesis focuses on.

There is not yet a system which would reliably combine risk assessment and flooding prediction features to a countermeasure advice to improve the situation on board. Thus, the objective of this thesis is to identify the most feasible counteractions on a cruise ship to combat a flooding situation enhancing the survivability of the ship and to be able to present these in a prototype graphical user interface of NAPA Emergency Computer.

Feasible counteractions are identified from the reviewed accidents and the scientific literature. The most promising countermeasure to prevent progressive flooding and especially up-flooding after closing of watertight doors is closing of certain fire doors. The effect of that on the development of a flooding case is studied with simulations in NAPA ship design software through four probable extensive damage cases a cruise ship can encounter and with different fire door statuses.

The simulations showed that closing of fire doors on the bulkhead deck above the damaged compartments between staircases and the service corridor has a very significant effect on increasing the time-to-capsize, in the best case with several hours by closing only one fire door in the SHOULDER 1 case.

A logic for suggesting the right fire doors to be closed is formed in the end of the thesis and the countermeasure advice is sketched to a prototype graphical user interface of NAPA Emergency Computer.

Keywords Decision support system, cruise ship, damage stability, countermeasure, fire doors

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Diplomityön tiivistelmä

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Tiivistelmä

Useita sotalaivoille ja risteilijöille suunnattuja päätöksenteon tukijärjestelmiä on kehitetty viimeisen noin kymmenen vuoden aikana avustamaan laivojen miehistöjä vauriotilanteessa. NAPA Emergency Computer, johon tämä diplomityö keskittyy, on Napa Oy:n kehittämä matkustajalaivoille suunnattu päätöksenteon tukijärjestelmä laivan haavoittuvuuden monitorointiin ja vuoto- sekä selviytymisarvion tekemiseen, mikäli laivan vuotovesisensorit havaitsevat vettä.

Päätöksenteon tukijärjestelmää, joka luotettavasti yhdistäisi riskiarvio- ja vuotoennustusominaisuudet ohjeistukseen hyödyllisistä vastatoimenpiteistä vauriotilanteen parantamiseen ei vielä ole kehitetty. Täten diplomityön tavoitteena on selvittää hyödyllisimmät vastatoimenpiteet risteilylaivalla, jotka tähtäävät laivan selviytyvyyden parantamiseen, sekä muodostaa prototyyppi NAPA Emergency Computerin graafisesta käyttöliittymästä, jossa nämä vastatoimenpiteet esitetään.

Eri vastatoimenpitedien kannattavuutta arvioitiin tutkittujen onnettomuusraporttien sekä tieteellisten julkaisujen perusteella. Lupaavimmaksi vastatoimenpiteeksi estämään veden leviäminen laivan sisällä vesitiiviiden ovien sulkemisen jälkeen osoittautui palo-ovien sulkeminen. Sen vaikutusta vuototilanteen etenemiseen tutkittiin simulaatioilla NAPA-laivasuunnitteluohjelmistossa neljän risteilijälle todennäköisen laajan vaurion sekä erilaisten palo-ovien sulkemisten kombinaatioilla.

Simulaatiot osoittivat, että palo-ovien sulkemisella laipiokannella vaurioituneiden osastojen yläpuolella portaikkojen ja pääkäytävän välillä on erittäin merkittävä laivan uppoamiseen kuluvaa aikaa pitkittävä vaikutus. Parhaassa tapauksessa laivan uppoamiseen kuluva aika pitkittyi useilla tunneilla sulkemalla ainoastaan yksi palo-ovi SHOULDER 1 –tapauksessa.

Diplomityön lopussa muodostetaan logiikka, jolla suljettavia palo-ovia ehdotetaan. Vastatoimenpideneuvo esitellään prototyypissä NAPA Emergency Computerin graafisesta käyttöliittymästä.

Avainsanat Päätöksenteon tukijärjestelmä, risteilijä, vauriovakavuus, vastatoimenpiteet, palo-ovet

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Henri Peltola

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Acronyms

A	Area of an opening
$A_{leakage}$	Leaking area of a door
$A_{submerged}$	Submerged area of a door
B	Breadth of a ship
C	Coefficient for navigational status
C_d	Discharge coefficient
D	Damage location compared to midship
F_{evac}	Evacuation factor
F_{ext}	Flooding extent factor
$FL(x)$	Floodable length function
GM	Metacentric height
$GM0$	Metacentric height without free surface correction
GM_{corr}	Free surface correction of metacentric height
GZ	Righting lever
GZ_{max}	Maximum righting lever
H_{coll}	Collapsing pressure head of a door
H_{eff}	Effective pressure head
H_{leak}	Leaking pressure head of a door
K	Heeling factor in s-factor calculations
L_{BP}	Length between perpendiculars
L_{flood}	Length of flooded compartments
N	Number of affected watertight compartments
R_{evac}	Ratio between required and available evacuation times
T	Draft of a ship
T_A	Available evacuation time
T_R	Required evacuation time
T_0	Required evacuation time at zero heel
a_{ratio}	Leaking area ratio
h_{gro}	Grounding damage limit
$r(\phi)$	Reduction factor
s_{final}	Survivability factor of SOLAS II-1 based on reserve stability
x_{flood}	Longitudinal center of the length of flooded compartments
ϕ	Heeling angle

Abbreviations

BHD	Bulkhead deck
BOSS	Bridge Office Support System
CFT	Counter-flooding tank
DB	Double bottom
DSRS	Damage Stability Recovery System
DSS	Decision support system
EC	Emergency Computer
EDSS	Emergency Decision Support System
GT	Gross tonnage
GUI	Graphical user interface
IMO	International Maritime Organization
KDSS	Knowledge-based Decision Support System
LRK	Laivanrakentajain kerho (Shipbuilders’ Club)
PS	Portside
SB	Starboard
SOLAS	Safety Of Life At Sea
VLog	Vulnerability Log
WT	Watertight

1 Introduction

1.1 Background

The amount of passengers on board a cruise ship can be today about ten times bigger than 40 years ago when one of the first ships intended only for cruising, “Song of Norway”, was built. Back then, about 700 passengers could fit on board, as today the number is about 7000. The ever expanding passenger capacity of cruise ships tends to increase the level of risk on board. If an accident should occur, more people are vulnerable to it than ever before. That is one of the reasons why safety at seas has gained more attention during the years. Regulatory bodies, such as International Maritime Organization (IMO), have set new guidelines affecting safety but also some ship owners have taken initiative independently to mitigate the risk of an accident at sea and also to improve their image in the eyes of potential customers.

Regardless of the measures to improve safety, accidents will take place also in the future and it is crucial to know how to react if one should occur. Several marine disasters have showed that one of the most important factors affecting the end result of an emergency is fast decision making when the accident is noted. The distress situation might evolve rapidly which demands for justified and quick decisions from the Master. In a highly stressful situation like that, it is challenging to find out the best actions to survive from the accident based just on experience and general seaman’s knowledge. A decision support system which assesses the current situation clearly and guides the user on possible actions is therefore of great help for the Master and ship’s officers.

One important aspect of ship safety is stability of the vessel. A damage scenario where the ship runs aground or is struck by another vessel causing flooding is one of the most alarming situations a vessel can undergo. Flooding presents a potential threat for the lives of everyone on board and it is vital to get it in control to prevent the vessel from sinking. This highlights the value of fast decision making and a need for a decision support system.

Computerized decision support systems (DSS) developed to aid the officers on board in a flooding situation aim to estimate the seriousness of the emergency thus providing valuable information for the officers to take the needed actions. There are several ways to approach the problem. Some systems are evaluating the situation based on pre-stored damage cases or manual definition of the damage whereas some others form their assessment with the help of real-time data from flooding sensors and watertight door statuses. There are also differences in how the results are presented. Some systems suggest actions that the officers should do to improve the situation whereas some others focus just on displaying the current flooding situation accurately and not discussing any corrective measures.

1.2 Scope and objectives of the thesis

This thesis will focus on a decision support system developed by Napa Ltd. called NAPA Emergency Computer (NAPA EC). The system is connected to ship's automation system and constantly monitoring the vulnerability of the vessel. If floodwater is detected in some compartment, NAPA EC will calculate a flooding prediction which estimates how the flooding will be progressing and how it affects the stability of the vessel. Based on this extensive information, the Master can decide about evacuation and other fit actions.

However, there is not yet a decision support system which could reliably inform relevant parties about the most feasible counteractions they should take in order to reduce the severity of a flooding situation. NAPA EC provides a reliable simulation about the progression of flooding in time-domain but it does not suggest any actions the crew should take. There is clearly a need for such system since the studied accident reports show that the actions taken by crews have not always been the most effective ones. Thus, the objective of this thesis is to identify the most feasible counteractions on a cruise ship to combat a flooding situation enhancing the survivability of the ship and to be able to present these in a prototype graphical user interface (GUI) of NAPA EC.

After presenting the background for the research i.e. existing decision support systems, especially NAPA Emergency Computer, and countermeasures utilized in accidents, the thesis continues with identifying other possible counteractions to decrease the severity of the flooding situation. All mentioned countermeasures are inspected in detail and their effectivity and related risks are studied. After that, the most feasible counteractions to combat flooding on board a cruise ship are suggested.

The feasibility of the counteractions is studied in NAPA using damage cases relevant to cruise ships eventually leading to sinking. These include extensive grounding damages to the foreship which result in flooding of the bulkhead deck. The ship model used in the simulations is based on the model B from Takkinen (2016). Aim of the simulations is to justify the use of the suggested counteractions by recognizing their effect on the damage scenario.

Finally, when the relevant counteractions have been defined, a logic for suggesting them to the crew is formed. The countermeasure advice obtained from this logic is then updated into a prototype GUI of NAPA EC that the end user will see.

2 State of the art

Ability to sustain battle damages is a key goal in naval ship designs. In addition the way a damage situation is handled on board plays a big role in the survivability of the ship. Continuous development in computer sciences led to the emergence of decision support systems for combatting different damage scenarios on board battle ships about a decade ago. The main counteraction presented in those systems is ballasting counter flooding tanks to obtain a more stable floating position for the damaged ship as stated by Lee (2006), Ölcer & Majumder (2006), Martins & Lobo (2011) and Hu et al. (2014). Choi et al. (2014) suggest also righting the damaged ship to the wave direction to prevent excessive motions.

In addition to DSSs aimed at suggesting countermeasures, there are also other approaches taken to provide advice for damaged naval ships. Varela & Guedes Soares (2007) utilize a virtual environment to aid the crew in combatting the flooding scenario. Calabrese et al. (2012) focus their efforts on monitoring the current status of all equipment on board and relying on an advisory card feature in case of a flooding damage.

Development of decision support systems for passenger ships has been driven more by rules and regulations than in the defense industry. IMO MSC.1/Circ.1245 sets the requirements for damage control plans and booklets for passenger and cargo ships. Damage control booklet is a good basis for creating advisory actions in a flooding situation to decision support systems. The introduction of Safe Return to Port rules and especially MSC.1/Circ.1400, defining a need for a stability computer on board assisting the Master in providing information about the operational situation when heading back to a port after a flooding incident, has increased the demand for DSSs. In addition, MSC.1/Circ.1291 demands for a flooding detection system for passenger ships built after 2010 which has enabled the development of flooding prediction tools utilizing flooding sensor data. A good example fulfilling and taking advantage of these rules is NAPA Emergency Computer.

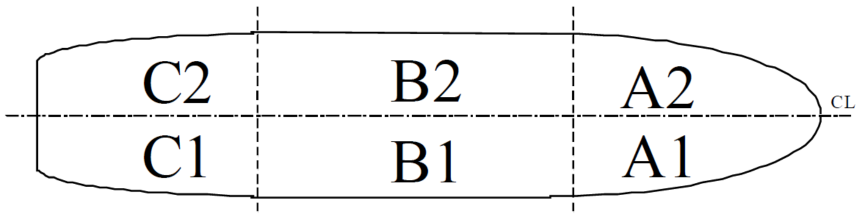
Also monitoring vulnerability of a cruise ship to flooding damage has been a popular topic in DSSs presented during the last decade. In addition to NAPA EC, systems by Jasionowski (2011) and Trincas et al. (2017) include measuring vulnerability to increase crew awareness and preparedness to a flooding incident.

Next, all the aforementioned DSSs developed for naval and passenger ships are presented in their publishing order except NAPA EC which is handled separately in Chapter 6.

2.1 A ballasting model for damaged ship by Lee (2006)

Lee (2006) suggests a simple ballasting model for improving stability and longitudinal strength of a damaged vessel. The model includes certain safety limits for heeling angle, trim and bending stress to which the current situation of the vessel is compared to. Based on the comparison, the system tries to calculate different ballasting options to meet the required safety criteria. Tanks used for ballasting in the calculations are prioritized as follows: ballast water tanks, void tanks, fresh water tanks and fuel oil tanks. These can be referred to as counter-flooding tanks (CFTs).

To reduce calculation time, the ship is divided into six zones, three zones for both sides of the ship as can be seen in Figure 2.1. Ballasting operations are suggested based on which zone the damage is located. The instruction is simply to de-ballast in the zone of the damage and ballast in the furthest zone from the damage.



Plan view of a ship

Damage zone A1	De-Ballasting	priority	A1, B1,
	Ballasting	priority	C2, B2, A2
Damage zone B1	De-Ballasting	priority	B1, (A1, C1)
	Ballasting	priority	(C2, A2), B2
Damage zone C1	De-Ballasting	priority	C1, B1,
	Ballasting	priority	A2, B2, C2

Figure 2.1 Ballasting zones introduced by Lee (2006).

All in all, the model is very simple and every Master should be able to make approximately the same decisions as the calculation method by Lee (2006) suggests. But considering a stressful emergency situation, instructed ballasting operations are welcome as part of a more comprehensive decision support system.

2.2 A case-based DSS by Ölcer & Majumder (2006)

Ölcer & Majumder (2006) present a case-based decision support system for damaged ships called COMAND-DSS focusing on identifying the best counter-flooding tanks to be filled in case of a flooding incident in order to correct the ship's posture. COMAND-DSS is similar to the DSS by Lee (2006) by suggesting different ballasting operations as the countermeasure to improve the stability of a ship after flooding damage. COMAND-DSS differs from the system by Lee (2006) by utilizing a database of damage cases and user input about the damage to give advice on the filling of CFTs.

The backbone of COMAND-DSS is a database of probabilistic damage cases calculated with NAPA. The cases are calculated for different loading conditions, covering the operation range of the vessel used, and two different watertight door statuses: all closed and intermediate. In intermediate condition, watertight doors in machinery spaces, stores and cabin areas are closed while others are open. This combination results in 13 984 different damage cases, for the studied ship, which are sorted based on their severity indices. Cases where the severity index is between 0 and 0.75 are selected for the database since only they can be affected by counter-flooding measures. This reduces the number of cases to 837.

In addition to the actual damage cases, the database used includes also the counter-flooding solutions for each damage case. The solutions present which CFTs should be filled to upright the vessel. The CFTs considered are ballast water, heeling, potable fresh water and fuel tanks. The counter-flooding solutions are constituted with two algorithms determining the optimum filling sequence of the tanks.

The user interface of COMAND-DSS is formed around a 3D model of the ship in question. The user can navigate freely in the model, visualize different floating positions and manually define the damaged compartments. Based on that, the system retrieves the best corresponding damage case from the database and displays in 3D model the CFTs to be filled to improve the floating position of the vessel as can be seen in Figure 2.2.

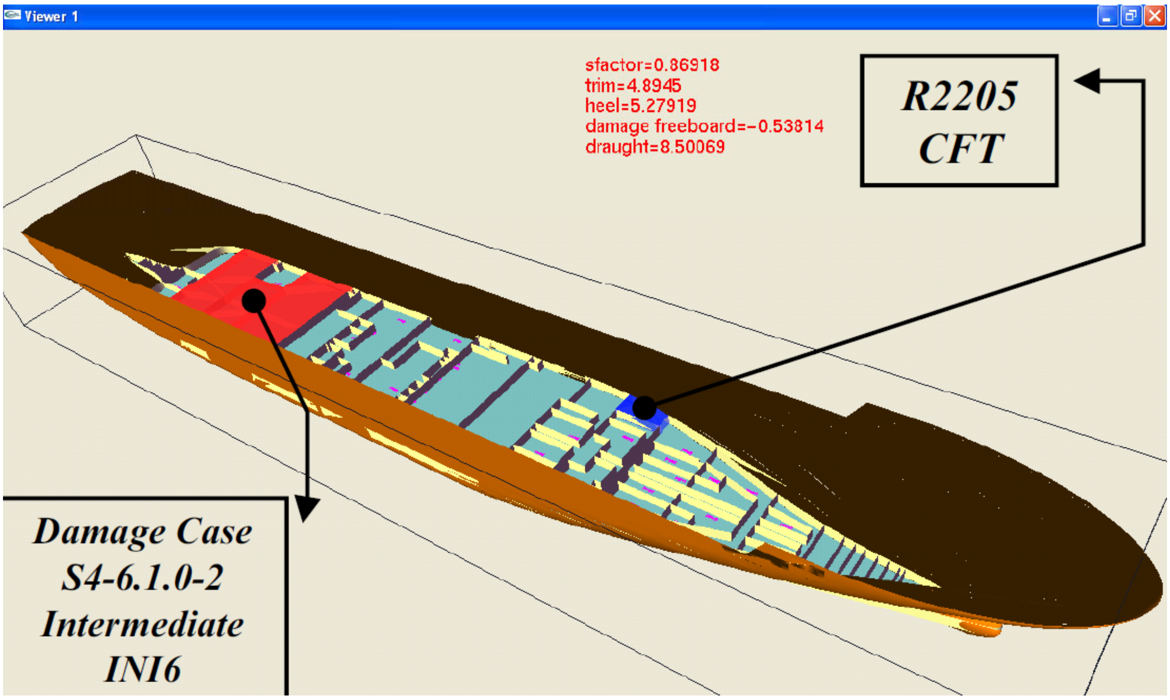


Figure 2.2 User defined damage and counter-flooding advice visible in 3D model by Ölcer & Majumder (2006).

Retrieving pre-stored damage cases from a database based on user input about the damage in a real flooding situation includes a lot of uncertainty and risks. The inaccuracy of damage definition by user might lead to the system selecting a damage case not corresponding to reality. Combining this with counter-flooding advice might create an even more dangerous situation than the flooding itself if ballasting is done to wrong tanks. This might have an opposite effect to stability than desired.

2.3 A virtual environment DSS by Varela & Guedes Soares (2007)

Varela & Guades Soares (2007) developed a DSS visualizing the progress of fire, contamination or flooding in a virtual environment. The approach is quite different compared to other DSSs because of the detailed graphical presentation of the geometric model used where the user can navigate with a fly-through camera. Figure 2.3 displays the user interface of the system. The user can define breaches to the hull, observe flooding simulation and operate equipment such as watertight doors from the virtual environment to prevent progressive flooding. The system is developed further to focus only on flooding emergencies by Varela et al. (2014).

Figure 2.3 Visualization of flooding in an engine room by Varela & Guedes Soares (2014).

The ship model used in the system consists of objects that have an effect on flooding in one way or another. Most prominent items in the model are “containers” and “connectors” which are essentially compartments and objects connecting them. Some connectors, e.g. watertight doors are intended to be controlled remotely by the user via the system. The user can also create new connectors to the model such as holes between compartments from where progressive flooding to adjacent compartments is possible.

The system by Varela & Guades Soares (2007) is able to do flooding prediction calculations based on data from flooding sensors using the aforementioned containers and connectors. It is not discussed whether this DSS is able to provide time-domain flooding prediction and e.g. present a time-to-capsize estimate.

The actual decision support functionalities of the system include identification of compartments subject to progressive flooding, isolation of compartments and definition of evacuation routes. Once water is detected in a compartment, the system displays which other compartments might be affected by progressive flooding. After this the user can isolate the flooded compartment by remotely closing open watertight doors from the virtual environment. Also effect of flooding to evacuation routes can be examined in the virtual environment.

One drawback of the system is the need for high computing power due to the complexity of the virtual environment and the ability of the user to navigate in there. It can be argued if the virtual environment really provides any value for the user to assist in decision making in a flooding emergency compared to the computing power needed.

2.4 Vulnerability log by Jasionowski (2011)

The time spent for decision making in an accident situation has proven to be a key issue affecting the final outcome of several distress situations as presented by Jasionowski (2011). He states that if crews of damaged vessels knew they were vulnerable to extensive flooding already before an accident occurred, they would be better prepared to make quick and feasible decisions when needed.

For this, Jasionowski (2011) suggests that the vulnerability of the ship to flooding should be presented constantly to the crew in terms of a VLog. Ship's current watertight integrity, loading condition and environmental conditions form the basis for the VLog calculations. The vulnerability is presented as "probability that a vessel might capsize within given time when subject to any feasible flooding scenario". This resembles the calculation of probabilistic damage stability of a vessel in the design stage. The level of vulnerability is displayed to the crew with traffic light colored diamonds for each compartment of the vessel, similar to visual representations of probabilistic damage stability calculations as can be seen in Figure 2.4. Thus, the main goal of the model is to keep the crew prepared for different damage scenarios and to see the effect of open watertight doors to the vulnerability of the vessel due to worsened watertight integrity.

The VLog is a good tool to maintain crew's awareness of the vulnerability of their vessel over time thus increasing their ability to make quick decisions, should an accident happen. The system is powerful when a quick decision about evacuation of a ship is needed. However, in flooding incidents where ship capsizing is not that evident, the system is of little help. It does not do real-time flooding prediction nor instruct the user about possible actions to improve the stability of the vessel.

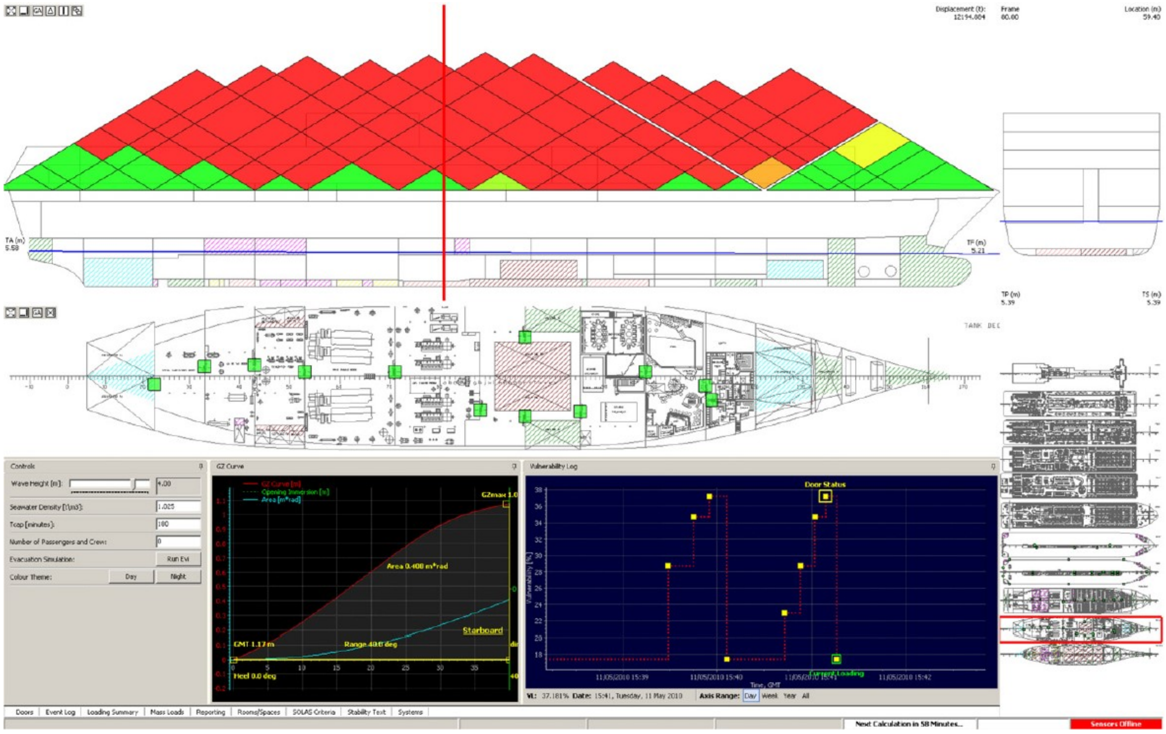


Figure 2.4 Screenshot of VLog by Jasionowski (2011).

2.5 Bridge Officer Support System by Martins & Lobo (2011)

Martins & Lobo (2011) present in their work a DSS called Bridge Officer Support System (BOSS) which resembles existing loading computers on board various vessels updated with functionalities to monitor maneuverability of the vessel and to give advice on ballasting options to improve vessel's stability after damage. BOSS is directed towards naval vessels which especially justifies the constant analysis of maneuverability.

The system is constantly reading data from ship's draft and tank gauging sensors to update the intact loading condition, which it compares to intact and damage stability criteria as well as strength limits. This functionality is similar to a regular loading computer on board. Based on the intact condition and other known characteristics of the vessel, BOSS calculates also maneuverability particulars.

When a damage occurs, the user has to define the size and location of the breach in the hull. Based on user input and connections defined between compartments in the model, BOSS calculates which rooms are going to be flooded. Based on this, a suggestion on how to distribute the vessel's pumping equipment to reduce progressive flooding is presented. In addition the system calculates which ballasting operations have to be done to achieve the best possible stability for the vessel as discussed earlier by Lee et al. (2006) and Ölcer & Majumder (2006). The user interface of BOSS where the damage definition is possible and the counteractions are presented is visible in Figure 2.5. The watertight subdivision and tank identification has been erased from the view most probably because of confidentiality.

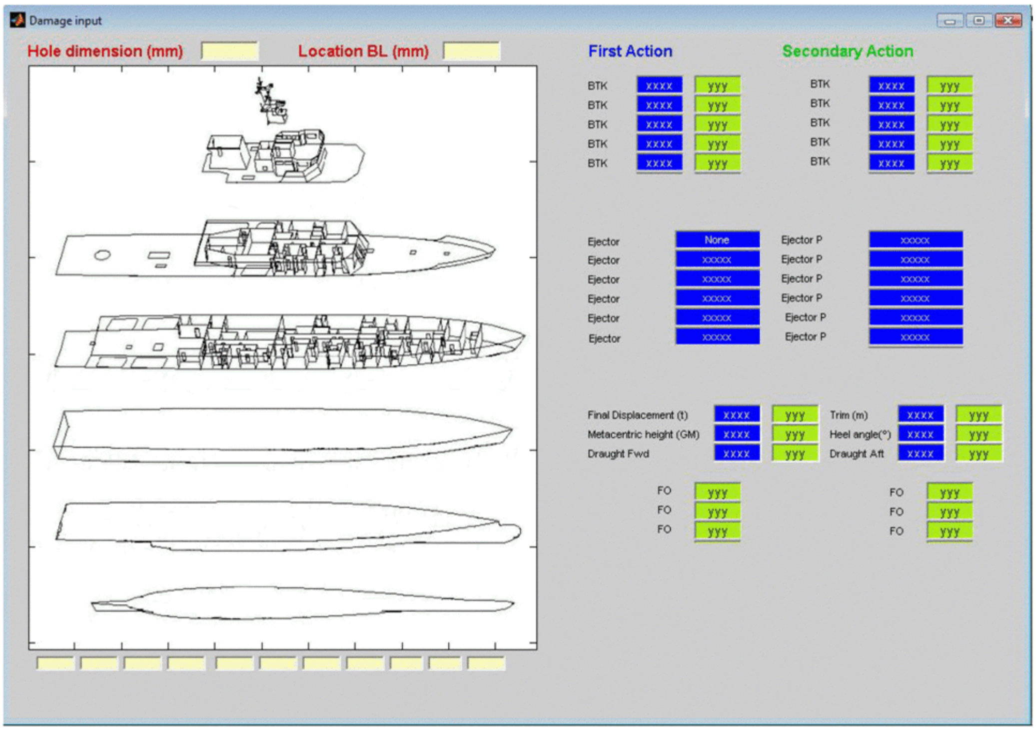


Figure 2.5 User interface of BOSS by Martins & Lobo (2011).

At the time of publication of the conference paper by Martins & Lobo (2011), BOSS was not able to do flooding prediction based on real-time data from flooding sensors, but the authors intended to add this functionality in the future. When that event realizes, the system could be taken as a comprehensive DSS.

2.6 A knowledge-based DSS by Calabrese et al. (2012)

Calabrese et al. (2012) have developed a knowledge-based decision support system (KDSS) for controlling various different damage scenarios on board a naval ship. The system is not limited only to assist decision making in a flooding situation but also in other emergencies such as a fire on board.

The KDSS is integrated into the vessel's damage control system and further to integrated platform management system, which enables receiving real-time data from e.g. flooding sensors and operating the equipment, such as watertight doors and pumps, on board. The approach used is based on "kill-cards" which display the current status of each compartment and suggest predefined actions in a damage scenario as can be seen in Figure 2.6. The kill-cards can be modified which allows the user to specify appropriate measures to fight against a damage. The source for actions presented in these cards could be e.g. a damage control booklet. Therefore, the kill-cards are essentially checklists to be followed in case of an emergency.

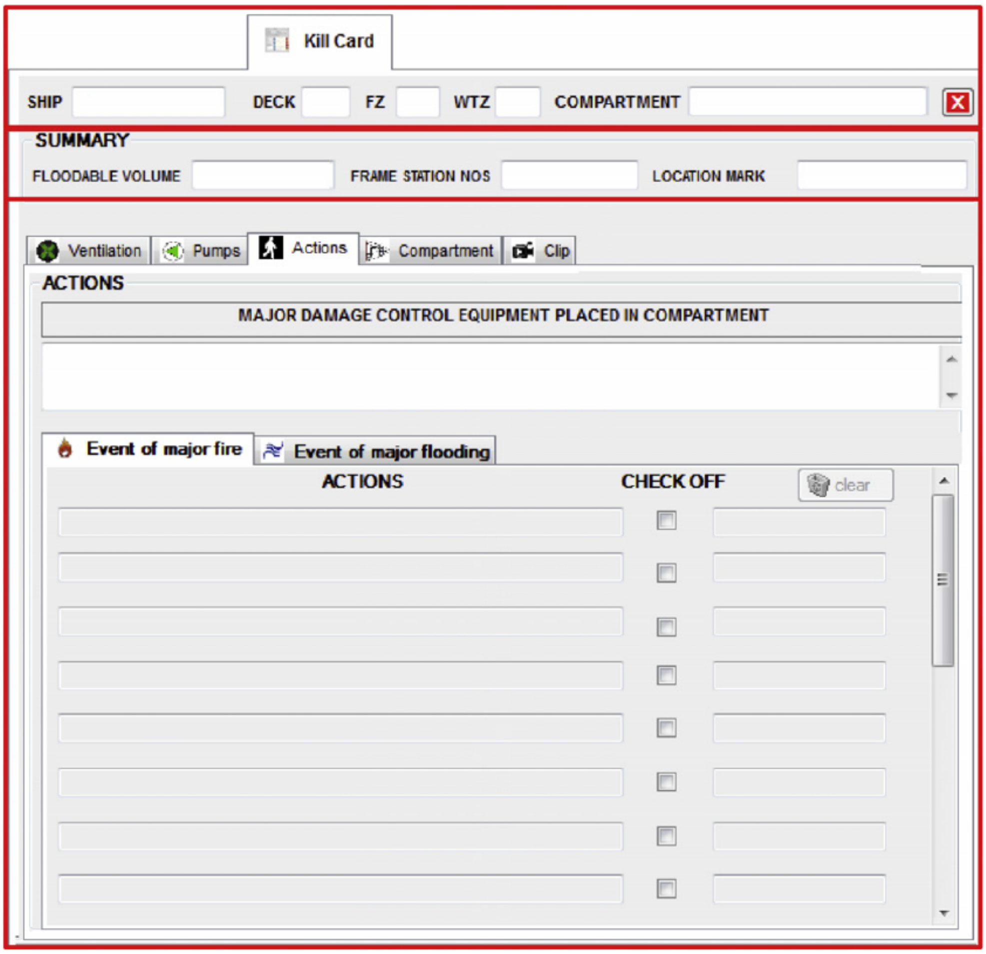


Figure 2.6 Structure of a "kill-card" used in KDSS by Calabrese et al. (2012).

The system is called "knowledge-based" because it utilizes knowledge from the actual design of the vessel, referring to structure and equipment, and the current runtime data e.g. from flooding sensors, as basis of the kill-cards. This knowledge is the basis of justified decision making. The KDSS by Calabrese et al. (2012) could be a good tool to monitor the status of a ship and its equipment and to present compartment specific countermeasures listed in a damage control booklet to mitigate the effects of a flooding scenario.

2.7 An onboard support system for damaged ships by Choi et al. (2014)

Choi et al. (2014) suggest a support system for damaged naval ships emphasizing the effect of the current sea state to the outcome of the damage situation. The system consists of a database including the ship characteristics, pre-defined damage cases and calculations of ship motions in different sea states. Since the system is developed for naval ships, also battle damages are included in addition to grounding and collision damages.

When the system is in use on board, damage can be defined manually or it can be read from ship's flooding sensors. Wave conditions such as heading and height should be known as well but the paper does not discuss how these are obtained. Based on pre-stored data, current damage suffered and current wave conditions, the system will evaluate the level of danger and present the safety status of the vessel with a red, yellow or green indicator. More detailed information about the situation is available in form of motional graphs of e.g. rolling angle and a time-domain prediction about how the situation will progress. This prediction can be used as an aid to decide about the evacuation of the vessel. Also polar charts are plotted to display ship motions in different wave heading angles. The polar charts can be used to align the vessel correctly to avoid excessive rolling motions which could capsize the ship. These features are presented in Figure 2.7.

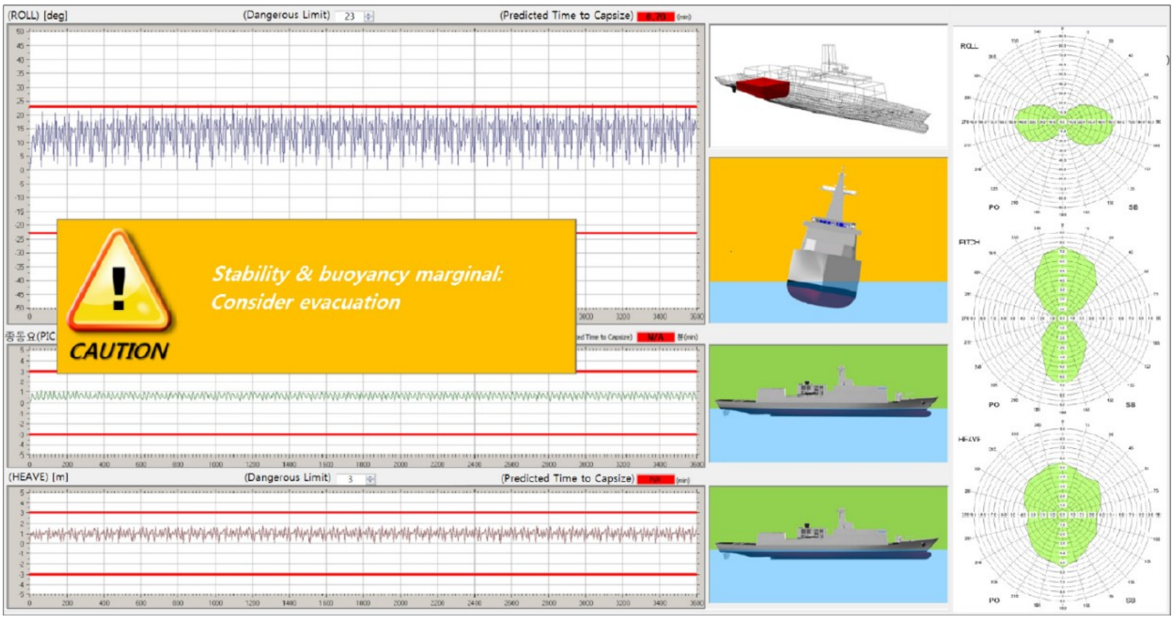


Figure 2.7 Motional graphs and polar charts by Choi et al. (2014).

The system by Choi et al. (2014) does not directly suggest any actions to prevent the spreading of ingress water inside the ship which prevents it from being a complete DSS suitable to be used alone in case of a flooding emergency. However, a combination of the KDSS by Calabrese et al. (2012) and the ship motions focused system by Choi et al. (2014) could be an effective DSS for a naval ship.

2.8 A counter-flooding decision model by Hu et al. (2015)

Hu et al. (2015) focused in their research on the corrective measures that can be taken in order to improve the stability of a damaged naval ship through correcting the vessel's floating position by filling or emptying certain CFTs as studied also earlier by Lee et al. (2006), Ölcer & Majumder (2006) and Martins & Lobo (2011).

One main objective of the article by Hu et al. (2015) is to find out the best way of estimating a good floating position which should be aimed at with the ballasting operations. The writers introduce tilt angle, which is a function of heeling angle and trim, to represent the floating position of the vessel. This is done to reduce the number of variables in the calculations, which speeds up the process of finding the suitable counter-flooding ballasting operations. The suggestions for the CFTs to be filled or discharged are obtained from a genetic algorithm which evaluates the fit of different combinations of ballasting operations based on the tilt angle resulting from the operations.

Since the model focuses only on posture control of a damaged ship, it cannot be used as such as a DSS to prevent progressive flooding. But the procedure of finding the suitable ballasting operations with the help of a genetic algorithm utilizing the introduced tilt angle might be useful as a part of a more comprehensive decision support system.

2.9 Delphi EDSS by Trincas et al. (2017)

Trincas et al. (2017) introduce a comprehensive commercialized solution for cruise ships monitoring risk levels associated to different phenomena on board called Delphi Emergency Decision Support System (Delphi EDSS). The system is also capable of doing time-domain flooding prediction without data from flooding sensors utilizing pre-stored damage cases and data from various sensors measuring the motions and drafts of a cruise ship. The biggest benefit of the system is the independency from flooding sensors which might not exist on older cruise liners, thus making the installation of Delphi EDSS feasible also for older vessels. However, if flooding sensors exist, they can be used to improve the accuracy of the flooding prediction.

In intact condition the Delphi EDSS can be used as a normal loading computer. It also constantly provides a complex risk assessment based on the ship’s current floating position, considering stability and strength, status of essential equipment in terms of Safe Return to Port regulations, capability to evacuate smoothly and ship motions considering amplitudes and resonance frequencies. The risk assessment is performed in a damage case as well. Calculated risk levels are presented with risk gauges and a diamond risk meter to visualize, which factor of ship safety currently poses the biggest threat to safe operations presented in Figure 2.8. The system can also spot the most dangerous flooding situation with the current loading condition and watertight door status, thus increasing crew awareness about the effect of open watertight doors, similarly as in Jasionowski (2011).

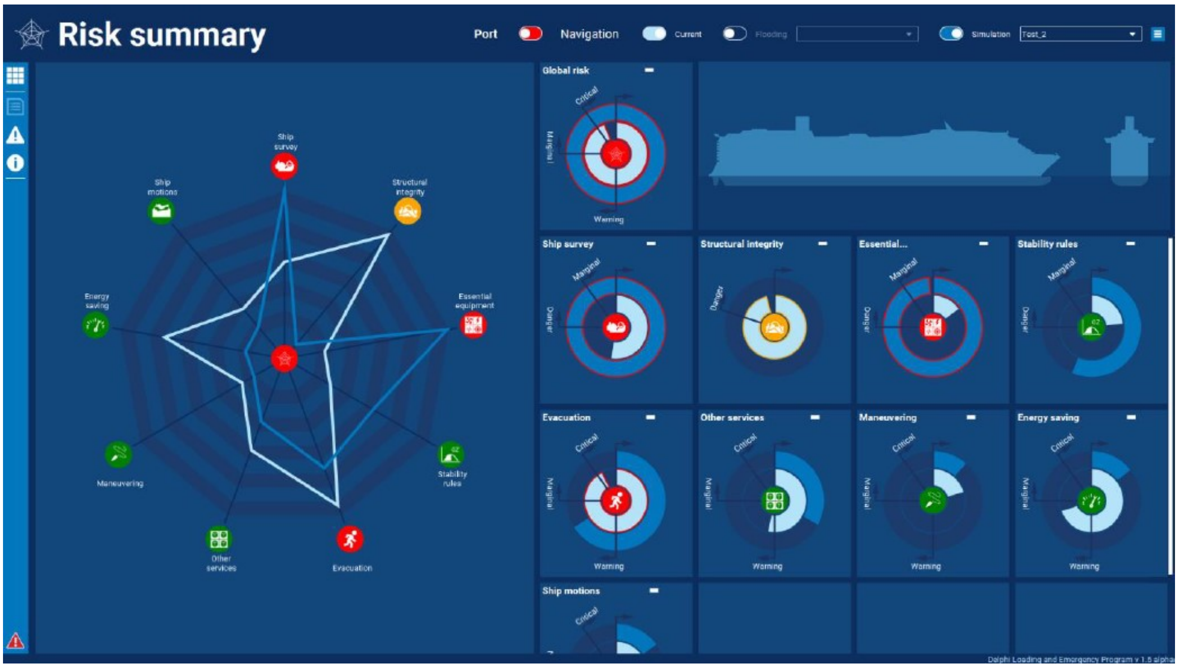


Figure 2.8 Risk gauge approach used in Delphi EDSS by Trincas et al. (2017)

The most interesting feature of Delphi EDSS is the ability to execute a flooding prediction without flooding sensors. There are two sources of data to enable this. The first one is a large database of different possible damage cases including the progression of flooding. The cases are calculated numerically for various loading and environmental conditions. The second data source are sensors installed on board monitoring ship's motions and floating position. When the sensors on board record sudden accelerations, caused by grounding or collision, increasing unknown deadweight with respect to current loading condition, or significantly varying heel and trim angle, the calculation is activated. The evolution of the floating position is compared to pre-stored damage cases in the database and a case with the best correspondence is selected as the initial prediction of the flooding progression. This includes estimating the size and location of the breach where water is flowing to the hull. As the situation develops, a case with better correspondence to reality is constantly updated in the system. Based on the flooding prediction, the system displays the possible time-to-capsize. Counteractions to increase the stability of the vessel are listed in specific advisory cards but they are not discussed in Trincas et al. (2017) in detail.

It is a huge challenge to provide reliable flooding predictions without flooding sensors. Thus, one big downside of Delphi EDSS is that the method it uses for predicting the water ingress from the modelled breach based on motion and floating position sensors has not been validated experimentally. Hence the calculation cannot be assumed to be accurate or reliable as of now.

3 Counteractions taken in accidents

After introducing different DSSs apart from NAPA EC, the thesis continues with a review of passenger ship flooding accidents and the countermeasures taken by the crews of damaged ships. Examining real-life flooding situations reveals the true need for counteractions an ideal DSS should suggest for the crew to be able to combat the flooding case.

One of the most important actions a crew can take after a flooding damage to the hull of the ship is to ensure the watertight subdivision of the ship by restricting the flooding only to the damaged compartments. This can be done by closing the watertight doors, provided that they were not closed already when the damage occurred. IMO MSC.1/Circ. 1564 coming to force on 1 January 2020 permits watertight doors to be open only for temporary passage or work in the vicinity of the doors but to be closed immediately when the transit or work ends. Closing of watertight doors is the simplest and most effective counteraction to take in a flooding incident, which should be very clear for every sailor. Nevertheless, passenger ships have sunk also during the 2000s due to open watertight doors. One tragic example is the sinking of a ropax vessel Express Samina after colliding into an islet causing a single compartment damage below the waterline (Papanikolaou et al. 2004). The vessel would have most probably survived the one compartment damage if the watertight doors were closed. They were not however, which resulted to Express Samina sinking in 50 minutes from the impact and loss of 80 lives.

In addition to the self-evident counteraction of closing the watertight doors, there are several other measures to take to combat the flooding situation. A dozen accident reports of passenger ships summarized in Table 3.1 where gone through to investigate counter-flooding actions taken by crews in damage scenarios. Next, findings from activities, other than closing of watertight doors, practiced in recent flooding incidents are discussed.

Table 3.1 Reviewed accidents

Name of the ship	Accident year	L_{BP} [m]	Type and extent of damage	Vessel sunk or beached?
Costa Concordia	2012	247.4	Raking, several compartments	Yes
Explorer	2007	64.9	Ice damage, one compartment	Yes
Commodore Clipper	2014	118.7	Raking, a few compartments (double bottom)	No
Monarch of the Seas	1998	236.0	Raking, several compartments	Yes
Urd	2012	155.8	Collision, one compartment & cargo hold	No
Express Samina	2000	107.0	Raking, one compartment	Yes
Pride of Telemark	2007	133.5	Collision, a few compartments	No
Queen of the North	2006	107.0	Raking, several compartments	Yes
Stena Jutlandica	2015	169.1	Collision, one compartment	No
Sally Albatross	1994	139.8	Raking, several compartments	Yes
Stena Nautica	2004	126.0	Collision, one compartment	No
Tallink	1995	115.1	Raking, a few compartments	No

3.1 Pumping

The most common action to reduce the rising volume of ingress water after a flooding damage is detected is pumping the water back to the sea. Pumping can be conducted either with a fixed bilge pump system or with movable pumping equipment.

Unfortunately, the capacity of bilge pump system or movable pumps has often been proven to be significantly smaller than the flow rate of the ingress water thus giving only some extra time for the crew to come up with better solutions to limit the flooding. This was the case e.g. in the sinking of a passenger vessel Queen of the North in Canada in 2006. Queen of the North grounded resulting in extensive hull damage and rapid flooding in several compartments. Bilge pumps were run in an attempt to pump out ingress water but the pumps "couldn't keep up with the flooding" and the ship sunk 80 minutes after the impact. (BC Ferries 2006)

The most recent reviewed accident where pumping was utilized as the major countermeasure to reduce the amount of ingress water was the sinking of an ice-strengthened passenger vessel Explorer in the Antarctica in 2007. The ship hit an ice floe which was harder than the vessel was designed for and caused most probably an about 3,6 meter long breach to the hull of the ship. Bilge pumps were started to pump out the ingress water. Also movable submersible pumps were used which meant that some watertight doors had to be kept open for the hoses between the pumps and the sea. This lead to water being able to spread also to undamaged compartments. This was the ultimate reason for the sinking of the vessel. One could argue that the vessel would not have been lost if the watertight doors were closed immediately, since the damage extended only to one compartment. In that sense, the focus to pumping and neglecting the effect of watertight doors caused the sinking. (Liberian Bureau of Maritime Affairs 2009)

Despite the two previously presented accidents where pumping proved to be in vain, there are also cases when it has proven as a successful way to save the ship from sinking or at least prolong the process. In 1994 a small cruise ship Sally Albatross suffered a raking damage in front of Porkkala peninsula on the Gulf of Finland. The resulted breach was long, it extended almost over the whole ship length and over several compartments. Using the bilge pumps and one moveable pump from a nearby icebreaker Voima slowed down the sinking of the vessel giving more time for evacuation and the rescue operation. Eventually Sally Albatross was towed to a shallow were it sunk. (Onnettomuustutkintakeskus 1994)

In 1995 south from Helsinki in the Kustaanmiekka strait passenger vessel Tallink ran over an underwater rock, which caused a breach flooding one compartment of the ship. The crew reacted swiftly and closed the watertight doors. However, they leaked significantly. Water was flowing into adjacent undamaged compartments also from inlets between compartments. Also in this case, an emergency bilge pump was used to pump out water from the undamaged compartments. Nearby ships provided also additional pumping equipment which settled the situation and ingress water level started to decrease in compartments where progressive flooding had occurred. The ship did not sink. (Onnettomuustutkintakeskus 1995)

It could be stated that pumping is feasible in the damaged compartment only if the breach is very small and the compartment can be easily accessed without a risk to life. It should be noted that pumping using movable equipment should not prevent closure of watertight doors as in that case, pumping and leaving the doors open might be worsening the situation through progressive flooding. Pumping of ingress water in undamaged compartments where water has been introduced through progressive flooding might be justified if efforts have been taken already to block leaking doors or openings in bulkheads for example.

3.2 Blocking leaks

A quite intuitive way to prevent flooding is trying to block the holes where water is leaking from. Blocking of breaches in the hull however is very difficult due to irregular shape and sharp edges of the hole due to the breaking mechanism especially in the case of a raking damage. Often the size of the rupture is also big causing a high flow rate which practically prevents plugging leaks in the hull. Fixing a breach caused by a collision with another ship might prove to be easier since the shape of the hole might be more symmetrical compared to a grounding damage. For example House (2014) suggests that after a collision with another vessel, a temporary patch should be inserted on the breach until the damaged vessel is taken to port of refuge.

During the sinking of Explorer, the crew tried to locate and block holes in the hull which they believed to be about “fist sized”. They managed to block one of them using pillows from a cabin and sheet of plywood on top. Despite of the effort, water continued leaking from other breaches which could not be located inside the ship. The crew lowered a rigid inflatable boat to inspect the damage and cover it with a tarp but the breaches were not found from outside of the hull either. (Liberian Bureau of Maritime Affairs 2009)

However, ensuring watertightness of the internal hull structures such as bulkheads, inlets or watertight doors is most often doable. The leaking holes in internal structures are not often as irregular in shape, big and sharp as damages in the outer hull which makes clogging them possible. It has been reported in the accident report of the grounding of Tallink that wooden pegs were fitted to leaking holes in one bulkhead to prevent progressive flooding (Onnettomuustutkintakeskus 1995). However, the effect of the measure is not discussed in the report. Most probably it has slowed down floodwater accumulation at least to some degree to the compartment adjacent to the damaged one.

3.3 Preventing up-flooding

If successful, preventing ingress water from rising in the flooded compartment to higher decks via escape hatches and staircases is one of the most important countermeasures that can be taken in a flooding accident. That is because there is a risk that floodwater will rise to the bulkhead deck, in case of large enough damage, and start to spread to adjacent compartments due to the lack of watertight subdivision on the bulkhead deck. If this happens, down-flooding to undamaged compartments can occur on a big scale, though all watertight doors were closed under the bulkhead deck, leading eventually to capsizing.

One accident where up-flooding of the ingress water had been actively tried to be prevented is the grounding of cruise ship Monarch of the Seas in 1998 in the Netherlands Antilles. The ship hit a reef causing damage to about half of the double bottom tanks and a few compartments on tank top. Watertight doors were closed after which up-flooding was tried to be prevented by closing escape hatches in two damaged rooms. Also a steel plate to prevent up-flooding was welded in one staircase where water was about to rise on the bulkhead deck visible in Figure 3.1. These actions most probably slowed down the progress of floodwater inside the ship and gave more time for evacuation. Before the flooding escalated on the bulkhead deck the Master decided to ground the ship on a shallow sandbar. (USCG 2003)

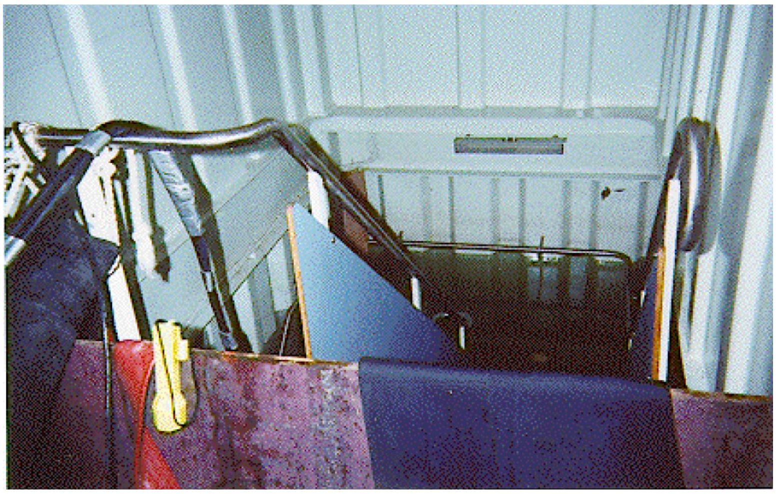


Figure 3.1 Welded steel plate to prevent up-flooding from a stairwell on board Monarch of the Seas (USCG 2003).

3.4 Discharging swimming pools

Several swimming pools on cruise ships are usually located high on the sun decks of the vessel. If filled with water, they increase the vertical center of gravity of the ship, thus decreasing the height of metacenter and worsening stability. They also create unwanted additional free surface moments. An easy way to improve stability in an accident situation on board a cruise ship is emptying these high located pools.

In the Sally Albatross accident, a swimming pool located on deck 9 was emptied when the crew realized the ship will sink (Onnettomuustutkintakeskus 1994). It is hard to tell how much it affected the situation but at least it improved the stability a little. The positive effect of discharging high located swimming pools is emphasized on cruise ships with several pools at the top decks.

3.5 Maneuvering

In cases where a ship has suffered a damage on either side of the hull and wind is causing a list submerging the breach deeper in the water, it might be beneficial to maneuver the ship regarding the wind direction to reduce the heeling angle on the damaged side. That is because the deeper in water the breach is located, the higher the flood rate of the ingress water due to higher hydrostatic pressure on the outside of the breach. To success in this attempt, the crew should know wind direction and location of the damage. E.g. if the breach is located on starboard side, the ship should be maneuvered so that wind is blowing from starboard side as well to lift the breach as high up as possible and limit the flooding rate.

During the sinking of Explorer, the Master tried to maneuver the vessel so that wind would have blown from the same side as where the damage was in order to decrease the list on that side thus bringing the damage as close to the waterline or even to the air to limit the flooding rate. The attempt was not successful because of lack of time. The sea was also quite calm during the accident which indicates absence of wind to create large enough heeling moment for the ship to list. (Liberian Bureau of Maritime Affairs 2009)

3.6 Ballasting/de-ballasting

Ballasting or de-ballasting was not used in any of the reviewed accidents immediately after the damage to improve stability. The crew of Explorer believed that changing their current ballast situation would not have had much positive effect on the stability of the vessel. This was because the ballast tanks were already mostly full and located low thus improving stability. The crew also believed that the tanks were too small to affect the list of the vessel. (Liberian Bureau of Maritime Affairs 2009) Thus, ballasting operations might be more feasible on board naval ships with denser subdivision, bigger counter flooding tanks and more powerful pumping systems compared to cruise ships to have sufficient positive effect on stability during the flooding. This could be seen also in the DSSs for naval ships where ballasting operations were often focused on.

Making too quick ballasting operations in the beginning of flooding might lead to dangerous situations. If a compartment extending over the whole breadth of the ship is breached the ship might start to heel on the side of the damage in the transient stage of flooding. At some point however, water level is high enough to return the heeling angle close to zero. If ballasting is begun before this to the heeling tanks opposite side of the damage, all water accumulated on the damaged side might suddenly flow to the ballasted side causing a dangerous moment which can in the worst case lead to capsizing.

For example Costa Concordia suffered damage on the port side and started heeling to that side as well. However, after half an hour, heeling changed from port to starboard and eventually the ship grounded with a starboard heel of about 30 degrees as can be seen from Figure 3.2. (Italian Ministry of Infrastructures and Transports 2013) If ballasting operations were started during the first half an hour by e.g. filling heeling tanks on the starboard side the ship would have sunk sooner and more lives would have been lost.

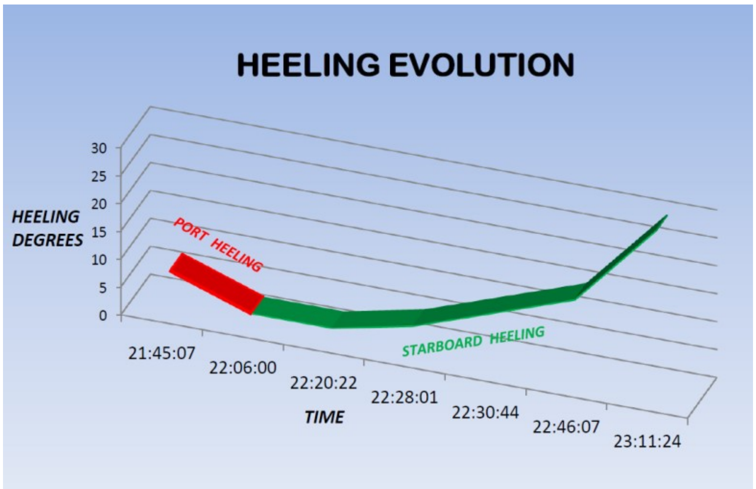


Figure 3.2 Heeling evolution of Costa Concordia showing the transfer from port to starboard heel. (Italian Ministry of Infrastructures and Transports 2013)

Ballasting becomes more important on passenger ships after the flooding is in control and salvage operations start. At that point, there is more time to ballast the ship to a suitable floating position for towing to a safe port.

4 Other possible countermeasures

In a highly stressful distress situation the crew does not necessarily act as it should and consider all possible options to reduce the negative effects of flooding. In addition to the countermeasures taken in real life accidents, there are also other possible ways to improve the survivability of a damaged ship.

4.1 Damage control booklets

IMO MSC.1/Circ.1245 sets the requirements for damage control plans and booklets that should be available on board. They provide information about the watertight subdivision of a ship considering also damage control efforts to prevent progressive flooding. Thus, damage control booklets should be the primary source of information for crews making decisions in a flooding situation. Despite of this, damage control plan was not used e.g. in the Costa Concordia accident (Italian Ministry of Infrastructures and Transports 2013). This indicates that the crew had not been aware enough about the documentation or that they found it too complicated to use.

Damage control booklets form the basis for counteractions that should be taken in a flooding scenario. The actions presented in them follow somewhat the list below:

1. Close watertight and semi-watertight bulkhead doors
2. Close shell doors and hatches
3. Close relevant valves which might cause progressive flooding
4. Determine the extent of damage, assess stability
5. Pump flooded compartments not connected to sea
6. Consider ballasting
7. Ship specific instructions (e.g. discharge swimming pools)

Relevant doors and valves are appointed for each compartment and the reader of the booklet can easily check what he/she needs to do in order to isolate a damaged compartment. All doors, hatches and valves are presented in a damage control plan which shows the locations of those devices on the decks of the ship. Actions listed in damage control booklets can be presented in a DSS with advisory cards dedicated for each compartment. This might help the crew to follow the actions listed in damage control plans.

4.2 Closing relevant fire doors

The first instruction in damage control booklets is naturally to close watertight and semi-watertight doors. In addition to these, there are also other doors on board that might slow down progressive flooding such as fire doors on the bulkhead deck. Closing of these non-watertight doors does not completely stop the spreading of water but it might prolong the time to sink which is extremely valuable for example from evacuation point of view. If the crew has information about the most probable route of progressing water, they might be able to seal for example a fire door by welding and prevent water from flooding through it to an adjacent undamaged compartment. This is important especially on the bulkhead deck where down-flooding in intact compartments might accelerate the sinking process dramatically.

Compartments below the bulkhead deck are separated by watertight bulkheads equipped with watertight doors. If suffered damage is large enough, floodwater might reach the bulkhead deck, where compartments are separated only with partially watertight bulkheads not extending through the whole breadth of the ship. Some of these are equipped with semi-watertight doors. All the other doors between compartments or vertical fire zones are fire doors. Damage control plans do not take fire doors into account in delaying progressive flooding because they are not designed for it. But as mentioned, they still have capability to slow down the flooding process from compartment to another and this feature should be taken into account when discussing possible countermeasures in a flooding situation. Closing fire doors in a flooding case is also recommended by House (2014).

Jalonen et al. (2017) presented results from the experiments of CTO on leaking and collapsing characteristics of different non-watertight doors on board as part of the FLOODSTAND project. The tests revealed that all of the tested A- and B-class doors start to leak immediately when exposed to water. The notations A- and B-class are related to the ability of structures to insulate heat due to fire. Most of the leaking happens through a gap between the door and the sill. An area ratio for each door was determined describing the ratio between the leaking and submerged area of the door:

$$a_{ratio} = \frac{A_{leakage}}{A_{submerged}} \tag{1}$$

, where a_{ratio} is the leaking area ratio
$A_{leakage}$ is the leaking area of the door
$A_{submerged}$ is the submerged area of the door

Leaking area ratio was dependent on the loading direction of the door and in some cases also on the pressure head. It was found to be at maximum about 0.05 which means that closing a fire door can suppress the flooding rate to 5 % compared to an open door. This is a very significant result justifying the effect of closing fire doors to prevent progressive flooding. Collapsing of the doors happened between 1 to 3.5 meters pressure head and it was independent of the loading direction. Figure 4.1 depicts the leaking area ratio results for A-class hinged fire doors and leaking of the doors.

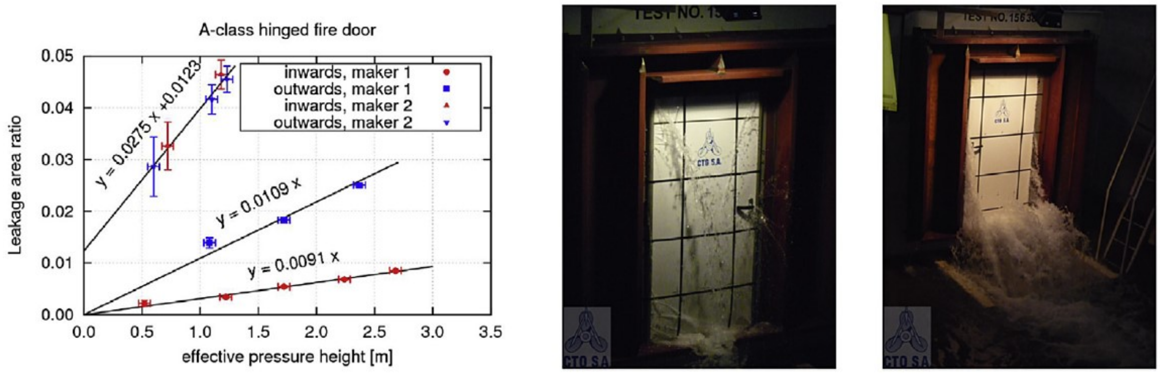


Figure 4.1 Full scale tests conducted by Jalonen et al. (2017) to measure leaking and collapsing characteristics of non-watertight doors.

Ruponen (2017) continued on the subject of paying attention to non-watertight doors in a flooding situation by simulating their effect on progressive flooding. Two damage cases were studied, a collision and an extensive grounding damage both with 250 different random combinations of non-watertight door statuses. The ship model used in the simulations was from the FLOODSTAND project by Kujanpää & Routi (2009). Leaking area ratios and collapsing pressures for doors were obtained from Jalonen et al. (2017). The results showed that fire door statuses have significant impact on the outcome of a flooding situation. Situations where all fire doors were closed did not provide the safest condition because of transient asymmetric flooding in the initial stages. Closed fire doors might at that point prevent a watertight compartment to be flooded evenly which results in a significant heel angle enabling up-flooding to the bulkhead deck. On the other hand, closing fire doors on the bulkhead deck considerably slows down progressive flooding. The best situation was found in a case where some fire doors were left open and some closed. Thus, the study suggests that fire doors below the bulkhead deck preventing equal flooding of the whole breadth of the ship could be left open and fire doors on the bulkhead deck should be closed in case of a damage situation.

Based on these results, a general instruction could be given to close all fire doors on bulkhead deck if flooding is detected. Special attention should be paid also to doors below bulkhead deck leading to staircases or escape hatches from where up-flooding could be possible, if there is enough time for closing these doors. It should be noted however that the doors in lower decks will collapse after 1 to 3.5 meter pressure heads which are most likely achieved quite fast after the damage has occurred. Most effective solution to prevent up-flooding would be to weld these doors permanently closed to make them as watertight as possible. Especially the gap between the door and the sill should be blocked. However, there is a significant risk of someone getting trapped behind such door. Therefore the crew should be absolutely certain that this risk does not realize when deciding to close a door permanently by welding or through other means. Welding requires also some time which might not be available in a rapidly evolving flooding situation.

Though Ruponen (2017) suggests that non-watertight doors below bulkhead deck possible of causing uneven transversal flooding leading to increasing list should be open, it might not be feasible for the crew to start going through those doors when flooding has started. Most of those doors on modern ships are also self-closing and cannot be kept open if there is e.g. no electricity on board because the mechanism to keep the doors open often utilizes electric magnets. Opening doors in rooms that might already contain ingress water takes also time which could be allocated more wisely on permanently closing the doors to escape hatches and staircases.

It should be noted that closing fire doors might increase evacuation times by restricting smooth flow of people during the evacuation phase. If the doors are closed in order to restrict progressive flooding, they can be opened for people to go through them during the evacuation and then shut again when the area has been cleared from people. However, this isn't possible if a door is shut permanently by welding or by other means. Welded doors don't only cause a risk of someone getting trapped but also increase the difficulty of evacuation leading to wasting precious time. Therefore, closing doors permanently should be avoided.

4.3 Methods of recovered buoyancy

Vassalos et al. (2016) claim in their work that more emphasis should be put to active measures on board to improve damage stability of ships rather than developing ever increasing design regulations. They introduce an alternative system for enhancing damage stability by reducing the permeability of damaged spaces with an expandable foam. The goal of the system is to recover the lost buoyancy of a damaged ship. This Damage Stability Recovery System (DSRS) can be installed to newbuildings and retrofitted to older vessels as well.

The system by Vassalos et al. (2016) aims to reduce the floodable volume of damaged spaces with foam that is injected to the spaces from a piping network. The foam is supposed to prevent ingress water from filling the damaged room. It also diminishes possible free surface effects of floodwater and stops progressive flooding. The system is operated by the crew and it is intended to be used on the most critical spaces from damage stability point of view. Vassalos et al. (2016) simulated the effect of the system in a ropax where lower cargo hold and the engine room were identified as the weak points regarding damage stability. They used the attained index A of probabilistic damage stability calculations in SOLAS Ch. II-1 (IMO 2009) as the key performance indicator measuring the effectivity of the system. By the permeability reduction originating from the possible use of the system, attained index A was able to be increased from 0.83 to 0.88.

The use of DSRS by Vassalos et al. (2016) should be considered with caution especially in engine rooms. On most ships the engines' air intake is inside the room. If a highly expandable foam is injected in such space, the air intake of the engines would be blocked and they could not be run. But if there is floodwater entering the room at high rates, the engines should be stopped at some point anyhow. At that point foam could be used to limit the floodable volume and reduce the free surface effect. Afterwards the foam can be dissolved with a solution included in the system.

To the writer's knowledge, the use of DSRS has not been validated in model test nor has it been commercialized or installed on any ship. The system clearly has potential to improve survivability of a damaged ship by restricting the amount of ingress water in damaged spaces and blocking progressive flooding. E.g. if water level is rising in a staircase and would eventually reach the bulkhead deck with severe consequences, the foam could be sprayed to block the staircase and prevent this from happening.

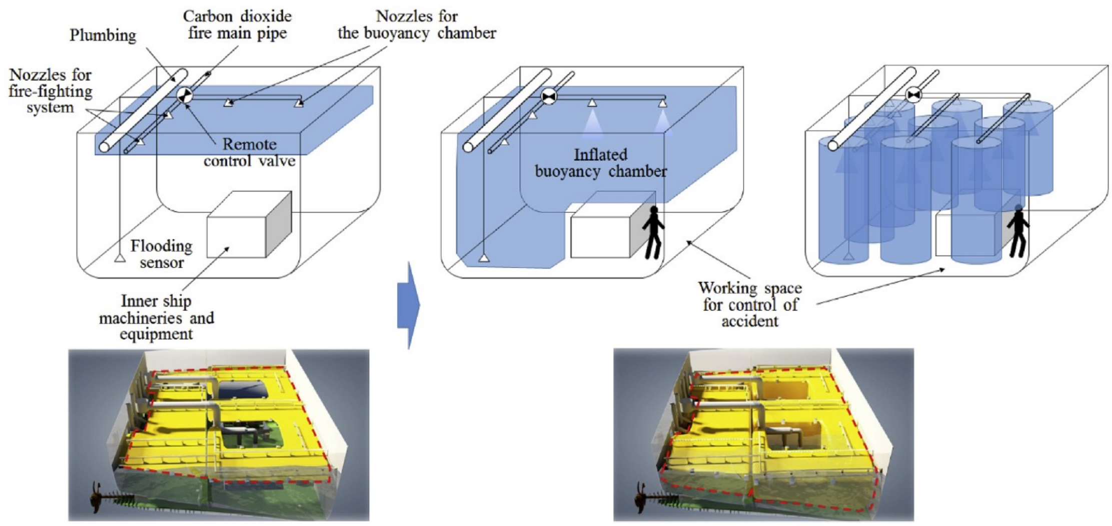


Figure 4.2 Different approaches to utilizing inflatable buoyancy recovery chambers studied by Kang et al. (2018).

Methods for recovering lost buoyancy have been developed also by Smith et al. (2011) and Kang et al. (2018) which both utilized inflatable buoyancy chambers instead of an expanding foam. Smith et al. (2011) studied the effect on structural strength of such a system placed in the double bottom of a tanker. Kang et al. (2018) did a more thorough review considering different inflatable bag sizes, shapes and arrangements for different rooms and all possible hazards related to the use of the system. The concept by Kang et al. (2018) uses the ship's firefighting water piping to distribute carbon dioxide to fill the buoyancy chambers when needed. Different buoyancy chamber arrangements are presented in Figure 4.2. The chambers are designed to enable crew operating in the room they are deployed. This means that they do not fill the rooms completely and thus cannot stop progressive flooding which reduces the usability of the system. However, they still reduce the floodable volume significantly thus improving the stability of a damaged vessel. They can also be used in an engine room as well unlike the foaming system.

5 Specification for a DSS for a cruise ship

Based on the existing DSSs, reviewed accidents and all possible countermeasures, a specification for a decision support system for countermeasures in cruise ship flooding case can be formed.

The accidents show that the importance of closed watertight doors was not clear enough for the crews of damaged vessels. This highlights the need for a vulnerability monitoring functionality as a part of the DSS. On the other hand, the crews were not maybe aware of the seriousness of the situations thus not closing watertight doors immediately. Estimating the survivability of a damaged ship based on visual observations of floodwater rushing in is a hard task. Using flooding sensors to measure the flood rate and predict progression of the situation would help the crew to better understand the severity of the damage case and available time for evacuation. A survivability assessment performed by a DSS would be of great help for the crew.

Delayed evacuation decision can be identified in several accidents that were reviewed. Time-domain flooding prediction with survivability assessment would sort out also this issue reducing the loss of life risk.

Regarding countermeasures presented in the existing DSSs, it can be interpreted from the accidents that counter-ballasting is not an effective method to significantly improve survivability of a damaged passenger ship. This is mostly because of the limited pumping capacity to perform quick enough liquid transfers. The suffered damage has often been quite extensive and counter-ballasting does not provide much of a relief in such situation and cannot be utilized to save a ship from sinking. Also too hasty decisions to ballast can have a negative effect on stability especially in the transient stage of flooding as explained earlier. Taking this into account, DSSs with only ballasting as a countermeasure are not suitable for passenger ships.

Maneuvering a damaged ship regarding wave and wind direction is not either the key to survival. It has been tried to be used e.g. in the Explorer accident without notable positive effects. Maneuvering might stabilize ship motions in rough seas thus improving effectivity of the crew taking damage control actions, but the positive effect on survivability has not been verified in any of the reviewed accidents.

The countermeasures suggested to the crew by a DSS should aim at stabilizing a flooding situation. This means that the floodwater volume inside the ship should be stopped from increasing. The easiest way to achieve this is isolating the damaged compartments hence ceasing progressive flooding. If only the damaged rooms were filled with ingress water and none of the intact spaces got flooded, hardly any of the reviewed accidents would have led to sinking. Thus, progressive flooding is the phenomenon that should be tackled in a damage scenario.

The countermeasures related to controlling progressive flooding apart from closing watertight doors are closing relevant fire doors and blocking leaks. This aims at preventing up-flooding to the bulkhead deck and further down-flooding to undamaged compartments. Incorporated in a DSS with flooding prediction, it would form a powerful tool to identify the most probable locations where the crew should concentrate their damage control efforts.

Discharging swimming pools on top decks is a countermeasure easy to carry out remotely from the bridge in modern cruise ships. It increases the metacentric height by lowering the center of gravity and reducing free surface moments. Thus the advice to do so should also be included in the DSS.

6 NAPA Emergency Computer

NAPA Emergency Computer is a decision support system developed by Napa Ltd. to monitor vulnerability status of an intact ship and provide a survivability assessment if flooding is detected (Pennanen et al. 2015). The evaluations are based on a detailed ship model and real-time data from ship's automation system, and require minimum amount of user input. The system is trusted among ship owners and installed on board several cruise ships of the major operators.

The graphical user interface of NAPA EC represents the vulnerability or survivability status of the vessel with a color coded risk gauge. In addition, the current floating position, number of open watertight doors or flooded compartments are presented together with interactive deck plans which visualizes the status of doors and flooding extent. The timeline of heel development is also accessible if water is detected. A view of the graphical user interface (GUI) of NAPA EC in intact mode is presented in Figure 6.1.

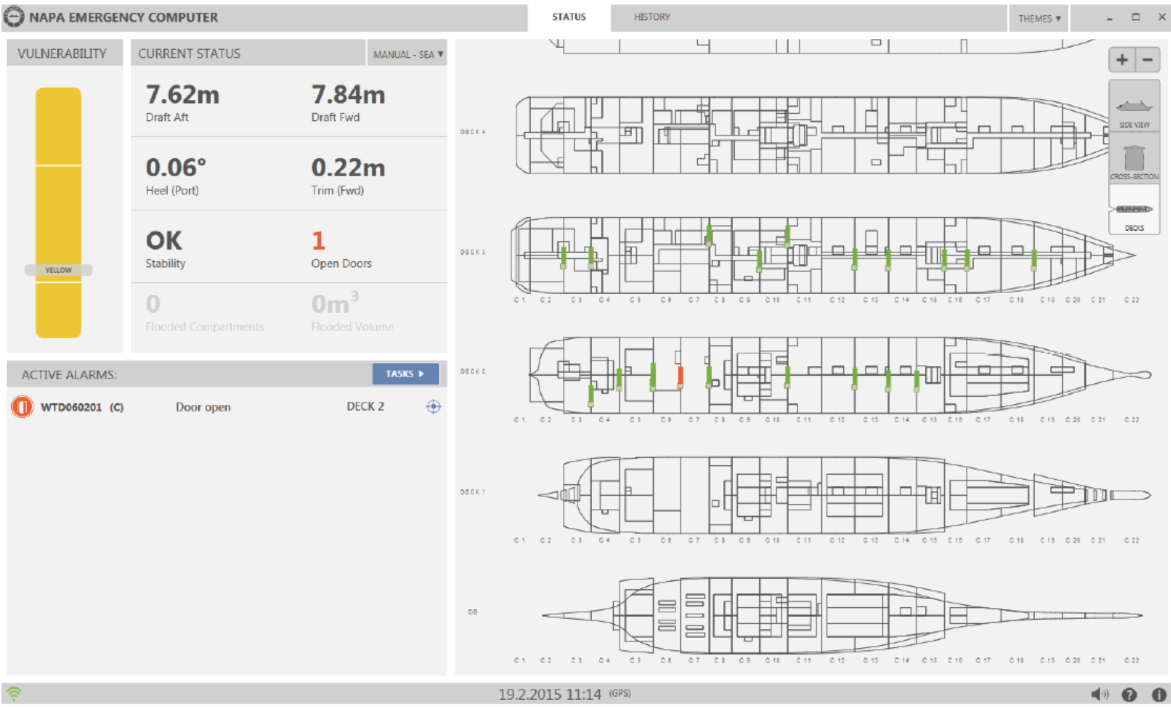


Figure 6.1 View of NAPA Emergency Computer in intact condition (Pennanen et al. 2015).

Maybe the biggest benefits of NAPA EC are the accurate and experimentally validated flooding prediction model it uses, and the clear user interface. However, at the moment the system does not directly suggest any actions the officers on board should take but only presents what will happen within the next three hours. The counter-damage activities listed in a damage control booklet can be incorporated to NAPA EC via an advisory card feature.

6.1 The ship model

The 3D ship model created in the NAPA ship design software forms the basis for the calculations in NAPA EC. NAPA model is a highly detailed representation of the ship hull covering also the inner subdivision. It includes all the details needed for precise intact and damage stability calculations.

The most fundamental objects in the ship model are rooms. These consist of all the tanks and dry spaces from the double bottom to one deck above the bulkhead deck. Also vertical connections such as staircases and escape trunks are modelled as individual rooms. In the upper decks, the modelling accuracy tends to decrease since some small non-watertight rooms do not have that much of an effect to the flooding prediction and they can be considered as a part of a bigger room they are in. From damage stability point of view, the most important features of rooms are their volume, shape and permeability or steel reduction. Permeability defines the maximum volume of water that can be filled to a dry space. Steel reduction is the equivalent of permeability for tanks. Permeabilities are dependent on the purpose of the rooms since it defines how packed the space is with different equipment or other items. For example stores have the lowest permeability because usually they are full of goods which reduces their floodable volume.

To be able to conduct flooding predictions, the rooms in the model have to be connected somehow. For this, the NAPA model contains openings between the rooms. These can be various types of doors, hatches or just connections to allow floodwater to spread from one room to another. Openings have several parameters determining their effect on the spreading of ingress water inside the ship. The most important parameters for openings are:

- Location of the opening
- Which rooms they connect
- Area of the opening
- Collapsing pressure head
- Leaking pressure head
- Area ratio
- Status (open/closed)

6.2 Vulnerability calculation

Vulnerability is a measure quantifying how vulnerable the ship is to a flooding damage. The factors affecting vulnerability are the amount of affected watertight compartments N through open watertight doors, the current navigational status C and loading condition. Vulnerability is measured on a scale from 0 to 1, as presented in Equation (2), with 1 being the worst value.

The values are color coded as follows: 0-0.2 green, 0.2-0.7 yellow and 0.7-1 red as presented in Table 6.1.

$$Vulnerability = min[1.0\,, C \cdot (N - 1)] \tag{2}$$

, where C is the coefficient for the current navigational status
N is the number of affected watertight compartments

Table 6.1 Color codes for different vulnerability levels

	$Vulnerability$
GREEN	0 – 0.2
YELLOW	0.2 – 0.7
RED	0.7 – 1

Open watertight doors significantly increase the vulnerability of the vessel to extensive flooding. Also Jasionowski (2011) utilized watertight door statuses as basis of vulnerability monitoring. However, it is not common that all watertight doors would be closed at sea on board a cruise ship because the crew has to move a lot between certain watertight compartments through the watertight doors. Hence, watertight doors are categorized by IMO to permit keeping some of them open even during sailing to ease everyday operations of the crew. According to Pennanen et al. (2015) the most important categories for passenger ships in MSC.1/Circ.1380 are:

- **Type A**: permitted to remain open during navigation
- **Type B**: may be opened during navigation when work in the immediate vicinity of the door necessitates it being opened, the door must be immediately closed when the task which necessitated it being open is finished
- **Type C**: may be opened during navigation to permit passage, the door must be immediately closed when transit is complete

NAPA EC takes this division of watertight doors into account when calculating vulnerability. Type A doors can be open without any negative effect to vulnerability whereas Type C doors are permitted to remain open only for a short amount of time e.g. couple of minutes without compromising vulnerability. The time limit for Type B doors is slightly harder to specify and should be reviewed case by case. If a time limit for certain door is exceeded, NAPA EC takes it as open thus exposing two watertight compartments. The statuses for each watertight door are obtained from the ship's automation system.

It should be noted that IMO MSC.1/Circ.1564 coming into force on 1 January 2020 does not include Type A doors anymore which means that no watertight doors are allowed to remain open during navigation for extended periods.

The navigational status has two options considered in the vulnerability assessment: either normal or increased risk due to e.g. poor visibility. In normal risk situation, the coefficient *C* obtains a value 0.25. In case of increased navigational risk, the coefficient is 0.5.

The last factor affecting the vulnerability level is the status of stability criteria and value of *GM* which is extracted from the loading condition to check if the criteria are fulfilled and minimum *GM* value exceeded. If yes, vulnerability is not affected, otherwise vulnerability obtains its worst value, 1.0. The current loading condition is calculated in the ship's loading computer and automatically transferred to NAPA EC. (Pennanen et al. 2015)

6.3 Breach assesment

The survivability calculation starts automatically when NAPA EC detects water in some compartment of the ship from flooding sensors. The amount and reasonable locations of flooding sensors are essential for accurate breach detection and flooding prediction as discussed by Takkinen (2016). In addition, the current loading condition and watertight door statuses are needed for the calculation. Fire door statuses can be utilized as well if they are available in the ship's automation system. (Ruponen et al. 2015)

When flooding has been detected, NAPA EC first makes an assessment on the size and location of the breaches in the hull where the floodwater originates from. This is done using the level rate data from flooding sensors taking into account the location of the flooded room. Reliability of the breach size estimation has been discussed by Carlstedt (2018) in detail. Location of the room is important since it has an effect on the most probable breach locations. For example, a double bottom tank suffers damage most probably to the bottom whereas a room on the side of the ship on the upper decks is more likely to be breached from the side. More precisely, a limit of *B/5* has been set for classifying rooms based on their locations. Here *B* is the breadth of the ship at the design draft. If a room extends outside of *B/*5 limit from the side, it is considered to be breached from the side. Then again if a room is located completely inside these borders the breach is most likely in the bottom of the room. However, bottom damages are found to exist only below certain level based on damage statistics. This grounding damage limit h_{gro} is (Bulian et al. 2016):

$$h_{gro} = 0.55 \cdot min(0.503 \cdot B^{0.636}, T) \qquad (3)$$

, where B is the breadth of the ship at design draft
T is the design draft of the ship

Rooms above h_{gro} and inside the *B/*5 limits are not considered in the breach assessment phase since damage penetration to those areas is not probable. The specified damage zones are presented in Figure 6.2. This kind of classification is done to accelerate the process of calculating the correct breach size and location in the room where floodwater is detected. Since flooding is still at its very initial stages at this point, all detected floodwater is assumed to come directly from the breach and progressive flooding is taken as non-existent to simplify the calculation. (Ruponen et al. 2017)

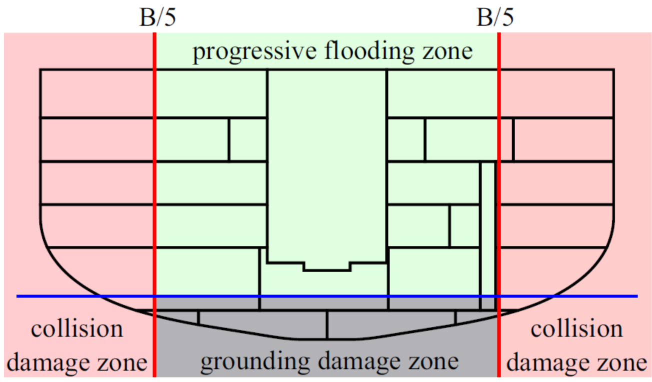


Figure 6.2 Different damage zones according to the specified limits as per Ruponen et al. (2017).

6.4 Flooding prediction

After specifying the initial breach locations, NAPA EC performs a progressive flooding prediction based on a novel pressure-correction algorithm developed by Ruponen (2007). A time step of 30 s is used in the breach assessment and flooding prediction (Ruponen et al. 2017). It is rather long but reduces the computation time. The prediction extends over a three-hour period and takes approximately three minutes to compute. It is constantly updated from the data from flooding sensors thus maintaining a high level of accuracy. The outcome of the prediction is an illustration of the development of the flooding extent on the deck plans of the ship presented in Figure 6.4, and a timeline of heel angle displaying key milestones such as angle of 15 degrees when lifeboats may not be lowered anymore presented in Figure 6.3. Also time-to-capsize is clearly presented if it occurs within three hours. (Pennanen et al. 2015)

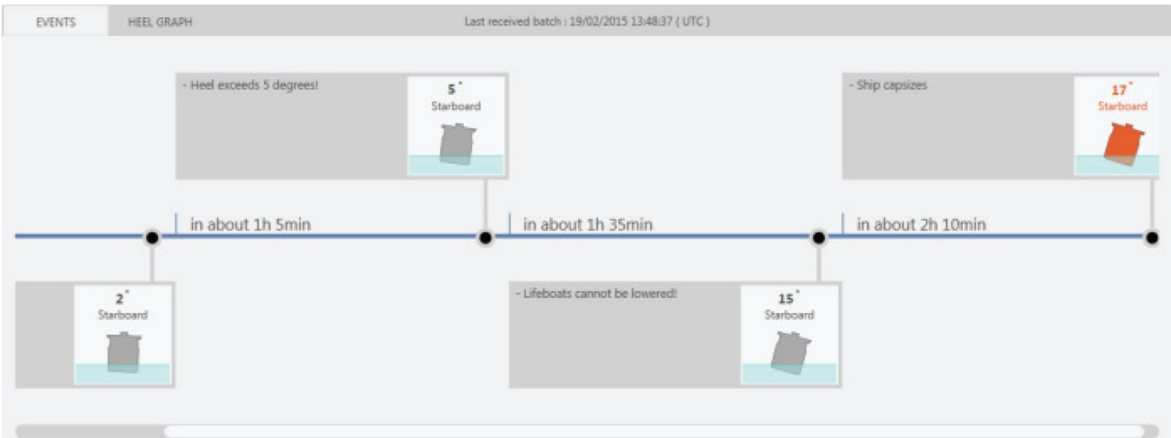


Figure 6.3 Timeline of the heel angle evolution displaying important milestones (Pennanen et al. 2015).

6.5 *Survivability assesment*

When the flooding prediction calculation is ready, NAPA EC carries out the actual survivability assessment. The main goal of this function is to evaluate the survivability of the people on board the ship. This is done by evaluating three different factors focusing on flooding extent, stability and evacuation. (Ruponen et al. 2015) Vessel TRIAGE categorization by Nordström et al. (2016) is utilized in visualizing the survivability level to the user of the system. Though Vessel TRIAGE does not consider evacuation as a threat to the safety of the ship, NAPA EC takes also that into account when displaying the color coded survivability risk gauge. The factor with the worst value defines the survivability level of the people on board the ship, as summarized in Table 6.2.

Table 6.2 Summary of the color codes for all factors affecting the level of survivability.

	F_{ext}	s_{final}	F_{evac}
GREEN	*Only 1 WT-comp flooded*	1.0	1.0
YELLOW	≤ 1	$0.8 \leq s_{final} < 1.0$	$0.8 \leq F_{evac} < 1.0$
RED	> 1	< 0.8	< 0.8

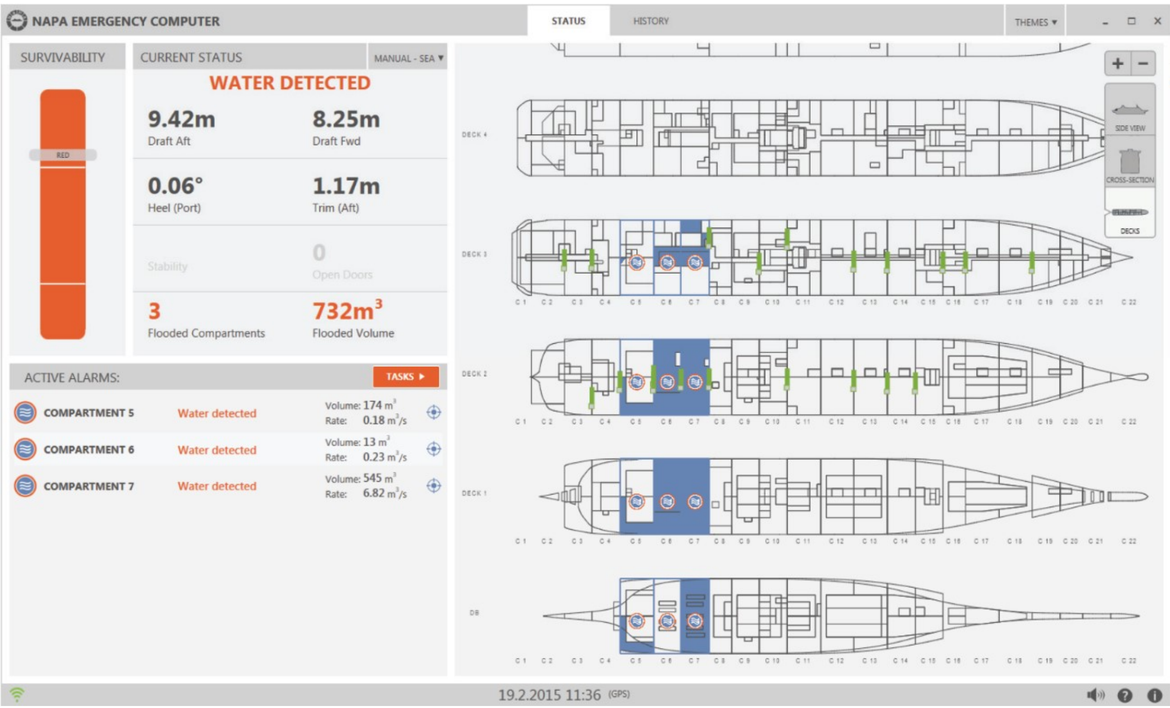


Figure 6.4 View of the colored survivability gauge and current flooding extent (Pennanen et al. 2015)

6.5.1 Flooding extent factor, F_{ext}

The survivability factor for flooding extent is dependent on the length of flooded compartments and pre-calculated floodable length curves from where the floodable length for current draft and trim can be interpolated. (Pennanen et al. 2016).

$$F_{ext} = \frac{L_{flood}}{FL(x_{flood})} \tag{4}$$

, where F_{ext} is the factor for flooding extent
L_{flood} is the length of flooded compartments
x_{flood} is the longitudinal center of L_{flood}
FL(x) is the interpolated floodable length function

F_{ext} obtains a green color if flooding is limited to single watertight compartment, yellow color if more than one watertight compartment is flooded but $F_{ext} \leq 1.0$ and red color if $F_{ext} > 1.0$. (Pennanen et al. 2016)

6.5.2 Stability factor, s_{final}

The stability factor is calculated with the s-factor formula from SOLAS Chapter II-1 Part B-1 Reg.7-2:

$$s_{final} = K \cdot \left(\frac{GZ_{max}}{0.12} \cdot \frac{range}{16}\right)^{\frac{1}{4}} \tag{5}$$

, where s_{final} is the stability factor
$GZ_{max} \leq 0.12$ is the maximum value of the righting lever *GZ*
$range \leq 16$ is the range of positive stability

,and

$$K = \sqrt{\frac{15° - \phi}{15° - 7°}} \tag{6}$$

, where $7° \leq \phi \leq 15°$ is the heeling angle

The upper limit for heeling angle has been set to 15 degrees since after that lifeboats may not be lowered anymore. Other limits are set to keep s_{final} between 0 and 1. The stability factor is green if $s_{final} = 1$, yellow if $0.8 \leq s_{final} < 1.0$ and red if $s_{final} < 0.8$. (Pennanen et al. 2016)

6.5.3 Evacuation factor, F_{evac}

Evacuation factor depends on the ratio between available and required evacuation times. The available time for evacuation is the time that it takes for the ship to reach a heeling angle of 15 degrees. The required time for evacuation is a function of heel angle since moving gets slower inside the ship with increasing heel angles. The required evacuation time with zero heel is 80 minutes for a passenger ship with more than three vertical fire zones according to IMO MSC.1/Circ.1238. (Ruponen et al. 2015)

$$F_{evac} = 1.0, \qquad \text{when } T_R/T_A \le R_{evac} \tag{7}$$

$$F_{evac} = \frac{\left(1-\frac{T_R}{T_A}\right)}{1-R_{evac}}, \qquad \text{when } R_{evac} < T_R/T_A < 1.0 \tag{8}$$

$$F_{evac} = 0.0, \qquad \text{when } T_R/T_A \ge 1.0 \tag{9}$$

, where T_R is the required evacuation time
T_A is the available evacuation time
$R_{evac} = 0.75$

And further due to heeling,

$$\int_0^{T_R} r(|\phi(\tau)|)d\tau = T_0 \tag{10}$$

, where $r(\phi)$ is the reduction factor due to heeling
T_0 is the required evacuation time at zero heel

The reduction factor reflects the increased required evacuation time due to heeling. NAPA EC utilizes a linear reduction factor function where the factor has a value 1 at 0 degree heeling angle and value 0.5 at 20 degree heeling angle. Thus:

$$r(\phi) = 1.0 - 0.025 \cdot \phi \tag{11}$$

, where ϕ is the heeling angle.

The evacuation factor is green if $F_{evac} = 1.0$, yellow if $0.8 \le F_{evac} < 1.0$ and red if $F_{evac} < 0.8$. (Ruponen et al. 2015)

7 Test method

As it was justified in Chapter 5 the counteractions performed by cruise ship crews should concentrate on limiting progressive flooding. The most important action naturally is to close all watertight and semi-watertight doors which are taken as closed in all of the following flooding simulations. But as mentioned earlier, in addition to that, there are also other possible ways to get the flooding in control. Most promising were closing other relevant doors, such as fire doors, desirably permanently by welding

In this part of the thesis, the effect of the crew closing certain non-watertight doors on the development of a flooding scenario is studied through different flooding simulations. This is done firstly to find out if closing of non-watertight doors is feasible and secondly to be able to construct a rule about which doors to close to have the biggest positive effect on controlling the flooding.

The simulations are performed in NAPA with a model of a modern cruise ship subjected to various damage scenarios. At first, a flooding simulation with an initial opening arrangement and a specified damage is ran and the results are listed. The progression of floodwater is inspected and possible doors to be closed on the way of the water are checked. After this, relevant doors are closed, which is essentially modifying a status of a door in the opening arrangement from open to closed, and the simulation is ran again to see if closing of the doors had any effect on the flooding case. A non-watertight door can be modelled as watertight by just simply removing it from the opening arrangement. This would represent a situation where the crew would be able to weld a non-watertight door closed.

7.1 The ship model

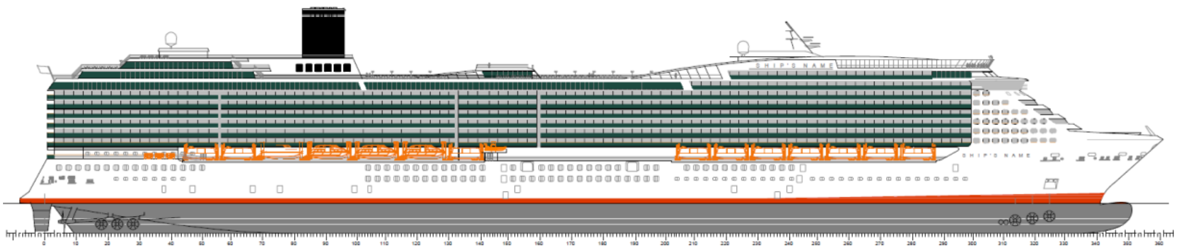


Figure 7.1 The concept cruise ship by Kujanpää & Routi (2009) used in the simulations.

The NAPA model used in the simulations is based on a 125 000 GT, 327 meter, 5600 person modern cruise ship developed for the FLOODSTAND project by Kujanpää & Routi (2009) depicted in Figure 7.1. The room arrangement has been modified from the original to correspond better to actual designs. The modifications include added double sides to engine rooms, more densely divided storage areas and added escape trunks and staircases to enable up-flooding from each watertight compartment. These adjustments are the same used in

Takkinen (2016). The original and the modified room arrangements can be found from Appendices 1 and 2.

The ship is divided into 22 watertight compartments below the bulkhead deck, which is deck 4. The watertight subdivision is presented in Appendix 3. There are watertight doors in the bulkheads below the bulkhead deck. The doors in the semi-watertight bulkheads on deck 4 are semi-watertight doors. The ship is modelled from the keel to one deck above the bulkhead deck.

7.2 Loading condition

The loading condition LOAD100 used in the simulations is created to represent a full load condition after leaving port with maximum draft. The fuel tanks are practically full and the ship has 5600 persons on board each of them weighing 100 kg with their luggage, an industry standard. A full load condition is selected for the study as cruise ships tend to sail most of the time with full occupancy. Hence an accident also happens most probably in such case. The trim and heel are close to 0 and the condition is stable and fulfills the most common stability criteria. Main characteristics of the loading condition are presented in Table 7.1. Details of the loads in LOAD100 can be found from Appendix 4.

Table 7.1 LOAD100 loading condition characteristics.

LOAD100	
Displacement	70521.0 t
Deadweight	13685.0 t
Draft, moulded	8.799 m
Trim	0.002 m aft
Heel	0.1 degrees starboard
GM	2.731 m
$GM0$	3.043 m
GM_{corr}	0.313 m

7.3 Initial opening arrangement

The opening arrangement used for the simulation is prepared to represent reality on board a cruise ship as accurately as possible. There are in total 357 openings in the model. Different door types with their most important parameters including area A, leaking and collapsing pressure heads H_{leak} and H_{coll} and area ratio a_{ratio} are presented in Table 7.2.

Table 7.2 Parameters of closed openings in the NAPA model.

Opening type	$A\ [m^2]$	$H_{leak}\ [m]$	a_{ratio}	$H_{coll}\ [m]$
Watertight doors	1.6	99	0.001	100
Semi-watertight doors	1.6	8.0	0.01	10
Cold room doors	1.6	0.0	$0.01 \cdot H_{eff}$	3.5
Lift doors	1.6	0.0	0.03	1.5
A-class fire doors				
Hinged, outwards	1.6	0.0	$0.03 \cdot H_{eff}$	2.5
Hinged, inwards	1.6	0.0	$0.02 \cdot H_{eff}$	2.5
Double leaf	3.2	0.0	0.025	2.0
Sliding	1.6	0.0	0.025	1.0

The H_{leak}, H_{coll} and a_{ratio} values for A-class fire doors, cold room doors and lift doors are defined in the research by Jalonen et al. (2017). Lift doors correspond to B-class doors in the publication by Jalonen et al. (2017). Watertight doors and hatches are taken as completely watertight with a leaking pressure head of 99 meters. The values for semi-watertight doors are based on the research by Ruponen & Routi (2011) and NAPA's recommendation. The variable H_{eff} in the table is the effective pressure head of water acting on the door. A value 0.6, an industry standard, for discharge coefficient C_d is used for all openings.

Connections between starboard and port side rooms are added to some areas since e.g. cabin areas are modelled as two rooms on both sides of the ship instead of one room extending over the whole breadth of the ship. By using separate starboard and port rooms connected with an opening, the damage stability results are closer to reality and e.g. free surface effect is not exaggerated. Because in reality, there is not a ship-wide free liquid surface in a cabin area limited by two bulkheads and the ship's sides due to complexity of the cabin area layout.

In addition to the parameters listed in Table 7.2, an important value affecting the outcome of a flooding prediction is the status of an opening, whether it is open or closed. If an opening is closed it affects the flooding prediction with all the values presented in Table 7.2. If an opening is set as open, it affects the flooding prediction only through its area through which floodwater can flow freely. Status of a specific door can be changed e.g. from open to closed to see what is the effect of that door on progressive flooding. This simulates the counteraction of crew closing for example a fire door after been advised to do so by a DSS. At first, it should be mentioned that all watertight and semi-watertight doors are closed, because that is the first thing the crew would do if flooding is detected. They are all remotely controlled on modern ships and can be assumed to be closed immediately when flooding is even suspected. Since the simulations are intended to study the effect of non-watertight doors on progressive flooding, their statuses are especially focused on.

The initial situation for non-watertight door statuses used in the simulations is formed by paying attention to the daily operation of the crew on board. Areas where the crew most likely passes through the most and works regularly have a high percentage of open doors. In general it could be stated that more doors are open on higher decks compared to lower decks. A general overview of the door statuses on different decks is presented in Table 7.3.

Table 7.3 Summary of opening statuses on different decks.

	Watertight doors	Semi-watertight doors	Cold room doors	Lift doors	A-class fire doors	Hatches
Deck 5					open	closed
Deck 4 (BHD)		closed	closed	closed	mostly open	closed
Deck 3	closed		closed	closed	mostly open	
Deck 2	closed			closed	closed	
Deck 1	closed				closed	closed

Next, the statuses of different opening types except from watertight and semi-watertight doors are explained in more detail and justified.

A-class fire doors make up the majority of the openings in the model and also the biggest variance in terms of their statuses. There are 190 hinged, 66 sliding and 17 double leaf A-class fire doors in the model. Hinged doors are more common in confined lower decks whereas the number of sliding and double leaf doors increases with the deck number.

On decks 1 and 2, all fire doors are closed. These are located mainly on the bottom of staircases leading to different types of stores and do not need to be kept open continuously. Also a number of doors to escape trunks are located on these decks and they are closed as well.

On deck 3, most of the fire doors are open. These include doors to staircases in the crew cabin areas and staircases leading to upper decks. All other fire doors on deck 3 are closed including e.g. entries to different stores and escape trunks.

Deck 4, which is the bulkhead deck, has a bit more complicated setup because of the variety of different rooms there. Also the main service corridor is located on this deck which means there is a lot of crew passing through continuously around the clock. Hence, all double leaf doors along the corridor are open. Also all fire doors in cabin areas and doors leading to any staircase or lift are open. The reader should note that lifts are equipped with lift doors with fire doors in front of them, at least in the crew areas. Most of the storage doors are open as well as doors to offices and security areas. Only doors to some technical rooms, ECR, workshop, medical center, escape trunks and doors between two storages are closed. Again, these spaces do not need to be kept open constantly.

Fifth deck contains already passenger spaces and in normal operation all fire doors there are open.

All cold room doors are closed because of their purpose, to keep the cold inside the room. All lift doors are closed as well which is the case also in reality most of the time. Especially during a flooding incident none of the crew members would use the lifts anyway. All hatches are closed because they do not need to be open continuously. All connections between starboard and port side rooms are open because they are modelled for calculation purposes only and should have an open status.

7.4 Damage cases

A variety of damage cases were inspected to find out how big a damage the ship has to suffer for ingress water to rise to the bulkhead deck and the ship to eventually sink. Damage cases leading to capsizing are of interest because the effect of countermeasures is easily quantifiable as an increased time-to-capsize. At this point the initial opening arrangement was used i.e. no countermeasures were applied yet. Time step used in the simulations to calculate the time-to-capsize was 60 seconds. This was selected instead of the 30 second time step used in NAPA EC because of faster simulation times and practically the same results as with the 30 second time step. Faster simulation times were appreciated in the search for suitable damages. To find out the accurate moment when water reaches the bulkhead deck in the beginning of a flooding scenario, a time step of 10 seconds was used for higher accuracy. All the scenarios were calculated in calm water.

Quickly it became evident that a collision damage with another vessel will not sink the studied ship. Collision damages are usually rather small in size and the resulted breach extends only over one or two watertight compartments as was noted already during the review of different accidents in Chapter 3. This kind of a damage is not capable of increasing the draft or heel enough to cause bulkhead deck flooding. Thus, collision damages are ruled out from the studied cases.

Since the ship has double sides in both engine rooms and denser subdivision in the aft compared to the other parts of the hull, realistic damages to the aftship neither cause sinking of the vessel. Denser subdivision mitigates the spreading of floodwater because of closed cold room doors for example. This restricts the variety of plausible damage cases able to sink the ship even more. As a result from that, the only rational damages would be located in midship or foreship which is sensible considering that a ship is normally sailing forward and the possible underwater obstacles would strike the fore part of the hull first.

The following damages presented in Table 7.4 are selected not only to present realistic breach locations leading to capsize but also to cover a range of different times-to-capsize.

This approach ensures that the effect of countermeasures is studied in rapidly developing situations as well as in more slowly progressing flooding cases. Ingress water rises to the bulkhead deck in less than 15 minutes in all the cases which shows that there is not time for the crew to perform countermeasures to restrict progressive flooding on lower decks than the bulkhead deck in case of damages leading to sinking. Hence all the efforts should be focused on the bulkhead deck.

The damages are so extensive that some crew cabin areas are flooded in couple of minutes after the impact. This means that most probably several lives are lost regardless of the countermeasures which are aimed to mitigate the number of lost lives. This should be kept in mind.

Table 7.4 Summary of the damage cases.

	SIDE	BOTTOM	SHOULDER	LOW SIDE
Breach location	side PS	bottom	side SB	side PS
Number of affected WT-compartments	6	9	4	6
Length	75 m	120 m	60 m	80 m
Longitudinal extension	125-200 m	140-260 m	200-260 m	110-190 m
Penetration	1.7 m	2.0 m SB	0-3.7 m	2.7 m
Vertical extension	5-6 m	0-2 m	7-9 m	1-3 m
Water on bulkhead deck in	12 min	2 min	4 min	9 min
Time-to-capsize	2 h 0 min	35 min	2 h 20 min	3 h 18 min
15 degrees of heel in	1 h 43 min	35 min	2 h 17 min	3 h 0 min

7.4.1 Extensive side damage, SIDE

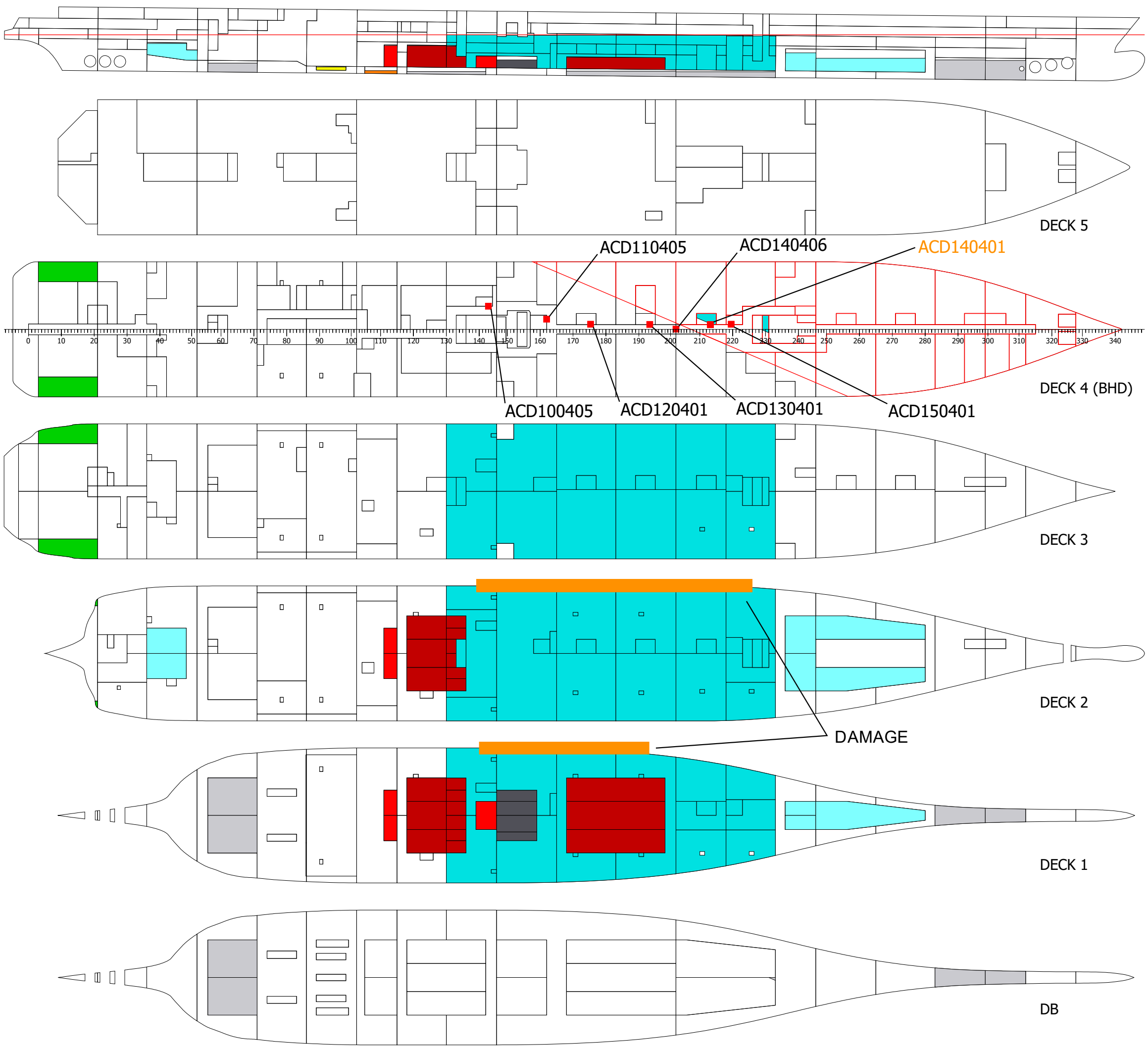


Figure 7.2 Floating position of the test ship with the SIDE damage when water reaches the bulkhead deck.

First of the studied damage cases is an extensive raking damage to the side of the ship. It is rather similar to the one suffered by Costa Concordia except longer and located slightly higher. The damage has a length of 75 meters extending over six watertight compartments with a height of one meter and a penetration of 1.7 meters. Breached spaces include dry spaces, stores and cabin areas on decks 1 and 2. With this damage water reaches the bulkhead deck in 12 minutes and the ship will capsize in 2 hours. The 15 degree heel angle, after which lifeboats may not be lowered, is reached in 1 hours and 43 minutes.

With this damage, water rises to the bulkhead deck from a staircase at frame 210. It starts to spread on the bulkhead deck through an opening ACD140401 which is an open fire door between the staircase and the service corridor with the text highlighted orange in Figure 7.2. This opening is one of the most important openings which should be focused on when thinking about closing of non-watertight doors in this damage case together with other similar doors above the damaged rooms on the bulkhead deck between staircases and the service corridor. These doors include ACD150401, ACD130401, ACD120401, ACD110405 and ACD100405. They are of importance because up-flooding to the bulkhead deck happens through them. By restricting the up-flooding of water, also the risk of down-flooding to intact rooms is decreased. ACD140406 is a double-leaf fire door on the service corridor which has potential in restricting the flow of water on the bulkhead deck but it does not directly prevent water from rising to the deck.

The floating position of the test ship with the SIDE damage at the time when ingress water reaches the bulkhead deck can be seen from Figure 7.2 together with the abovementioned openings. The red lines on deck 4 represent the area of the deck that is below the waterline. Doors marked red are open and doors marked green are closed. The same coloring rule is used in NAPA EC as green color is conceived as good and red as bad by most of the people.

7.4.2 Extensive bottom damage, BOTTOM

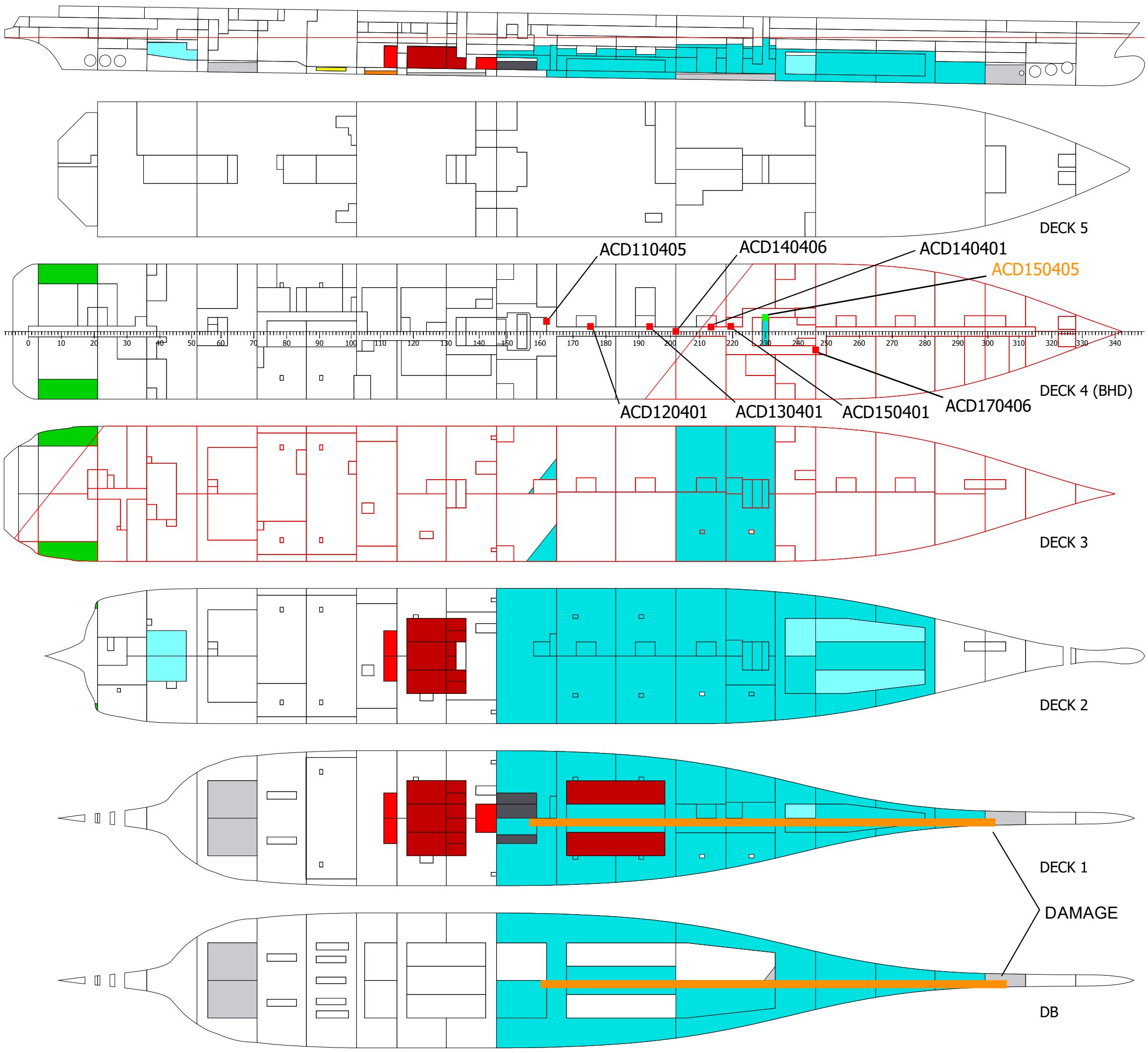


Figure 7.3 Floating position of the test ship with the BOTTOM damage when water reaches the bulkhead deck.

The second damage is a very long and deep bottom damage which resembles the accident of Monarch of the Seas except that this damage has a deeper penetration to breach also the rooms above the double bottom as presented in Figure 7.3. The breach is 120 meters long extending over 9 watertight compartments with a vertical penetration of 2 meters extending from the centerline to two meters starboard. The damaged rooms include stores on deck 1 in addition to tanks and voids in the double bottom and on deck 1.

Because of the enormous size of the breach, the test ship will sink very rapidly, in 35 minutes, which calls for swift advice from a DSS. There is water on the bulkhead deck already in two minutes after the damage, which means that there is no time for a DSS to start an accurate flooding prediction taking couple of minutes. This indicates that a DSS should have a functionality suggesting quick actions immediately when water is detected in some compartment, not after a time consuming simulation, in order for the crew to have even a slightest chance in saving the ship in such a disastrous situation.

Water rises to the bulkhead deck first from a laundry chute at frame 230 and starts to leak through an opening ACD150405 which is a closed fire door between the laundry chute and the service corridor with the text highlighted orange and the door marked green as closed in Figure 7.3. Since the door is closed, it should be welded to restrict the flow of water more effectively. But because the water is on the door already in two minutes, other options to restrict the spreading of water should be considered e.g. closing open fire doors between staircases and the service corridor as in the previous damage. These include ACD150401, ACD140401, ACD130401, ACD120401 and ACD110405. Also the double leaf fire doors ACD140406 and especially ACD170406 on the service corridor can be considered to restrict the spreading of water on the bulkhead deck if closed.

7.4.3 Extensive fore shoulder damage, SHOULDER

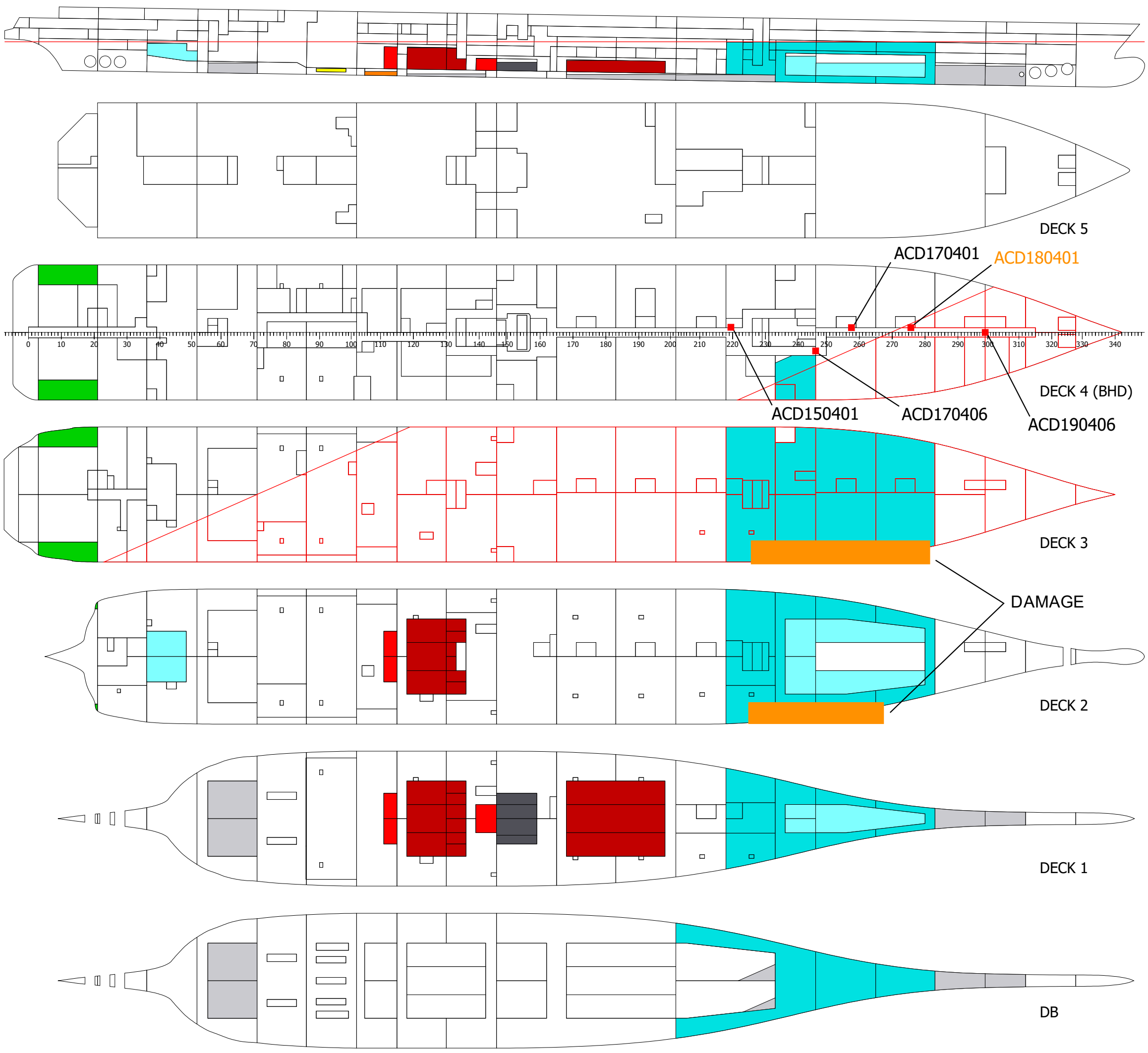


Figure 7.4 Floating position of the test ship with the SHOULDER damage when water reaches the bulkhead deck.

The third damage is located at the waterline on the starboard fore shoulder of the hull as presented in Figure 7.4. This would represent a ship colliding e.g. to an islet during poor visibility. The length of the breach is 60 meters extending over 4 watertight compartments with a vertical extension of 2 meters. The penetration of the damage is at maximum 3.7 meters in the aftmost part of the breach. The breach breaks voids on deck 2 and cabin areas on deck 3. This is the smallest damage and results to capsize in 2 hours 20 minutes. However, water reaches the bulkhead deck already in about four minutes after the impact.

Ingress water rises on the bulkhead deck from a staircase on frame 270. It leaks through opening ACD180401 which is an open fire door between the staircase and the service corridor with the text highlighted orange in Figure 7.4. All the water rising to the bulkhead deck flows towards the bow because of bow trim. It takes more than one hour for the water level on the service corridor to rise to the same level as the fire door ACD180401. This shows that regardless of the quick rise of the ingress water to the bulkhead deck, there is still plenty of time for the crew to close the door before it is too risky. This should be taken into account also in other cases and not reject a possibility of closing a door just because water is quickly on the bulkhead deck. Other fire doors between staircases and the service corridor above the damaged rooms are ACD170401 and ACD150401. Double leaf doors on the service corridor capable of restricting the flow on the bulkhead deck are ACD170406 and ACD190406 with more emphasis put on the latter which is able to restrict the flow to undamaged compartments if closed.

7.4.4 Long and low side damage, LOW SIDE

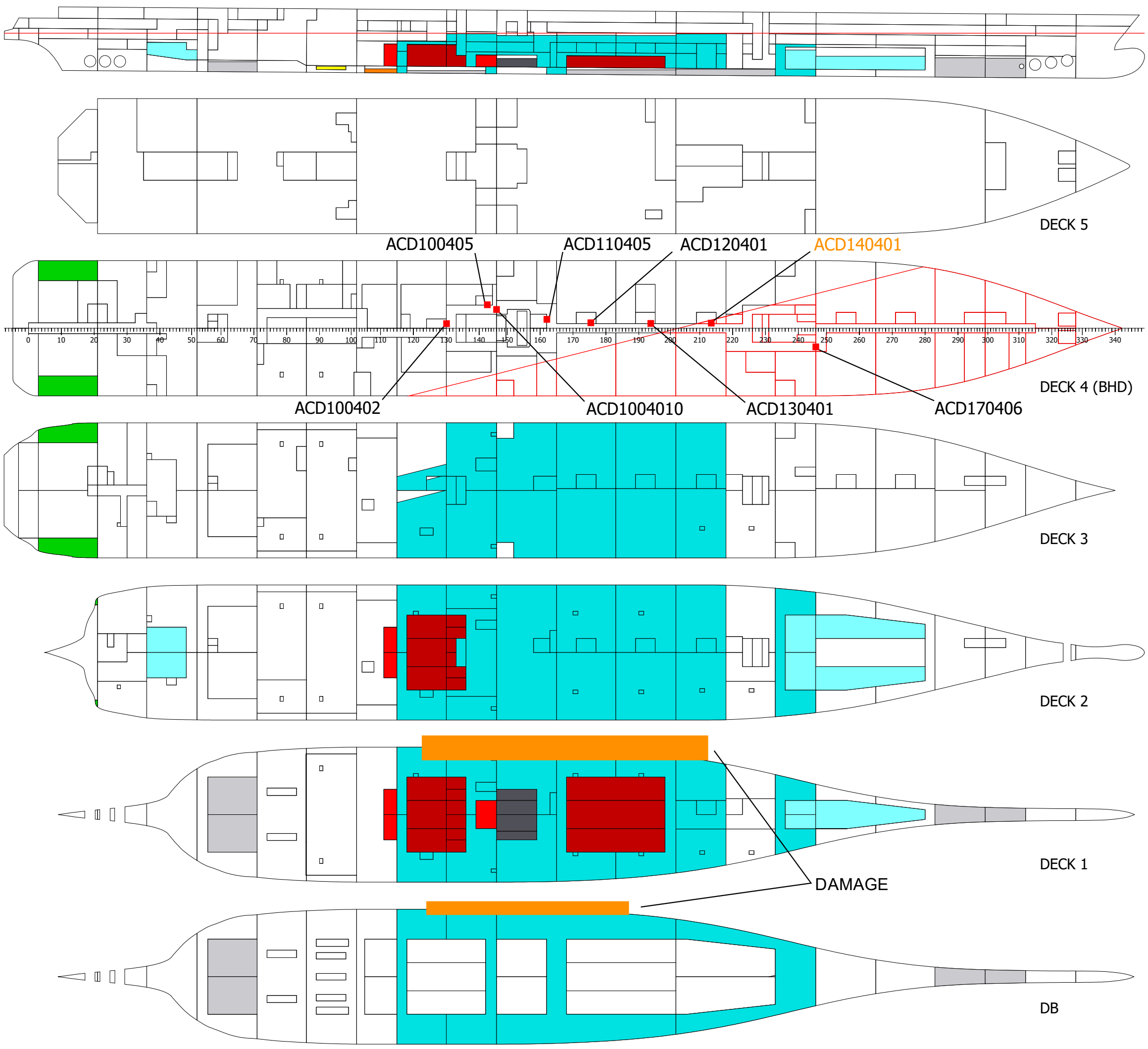


Figure 7.5 Floating position of the test ship with the LOW SIDE damage when water reaches the bulkhead deck.

The fourth and last of the studied damages is a long side damage located low in the hull breaching also double bottom tanks as presented in Figure 7.5. It is selected to the study because of its rather long time-to-capsize, 3 hours 18 minutes. The breach is 80 meters long extending over six watertight compartments with a transversal penetration of 2.7 meters and a height of 2 meters. Also this damage is very similar to the Costa Concordia disaster breaching also some double bottom tanks. Also the evolution of heel during the flooding is alike: port heel in the transient phase of flooding turning into starboard heel with the ship capsizing also to starboard.

Water reaches the bulkhead deck in a bit less than nine minutes from the staircase at frame 210 and opening ACD140401 which is an open fire door between the staircase and the service corridor with the text highlighted orange in Figure 7.5. This is the same location as in the first damage. Also here the fire doors between staircases and the service corridor are the key in controlling the flooding. These include ACD130401, ACD120401, ACD110405, ACD100405 and ACD100402. Also double leaf fire doors ACD170406 and ACD1004010 might limit the flooding on the bulkhead deck.

8 Results and analysis

Now as the loading condition, initial opening arrangement and relevant damage cases for the study ship have been determined, the actual flooding simulations can be performed. The goal is to find out the effect of closing of fire doors on the bulkhead deck on the time-to-capsize. Possible fire doors able to sufficiently restrict progressive flooding were identified for each damage case in the previous chapter. Results of the simulations are presented as heel evolution graphs.

8.1 Simulation cases

8.1.1 SIDE 1

Water rose to the bulkhead deck in 12 minutes with the SIDE damage and the initial opening arrangement from opening ACD140401 which is a fire door between a staircase at frame 210 and the service corridor. Since this is the first location where up-flooding to the bulkhead deck happens, the first simulation case SIDE 1 has opening ACD140401 closed. The situation is presented in Figure 8.1 where green marks a closed door and red marks an open door.

With this case, the simulation stops at 162 minutes which is 2 hours and 42 minutes and the ship capsizes. This is 42 minutes longer than the initial time-to-capsize in the SIDE case, which was exactly 2 hours. According to the flooding simulation, by closing just one specific regular hinged fire door on the bulkhead deck, the crew can buy 42 minutes more time to evacuate the ship! This is a significant improvement with that little effort. Evolution of the heel can be seen in Figure 8.4. The heeling angle starts to diverge from the initial case after the water has reached the bulkhead deck level at 12 minutes and cannot flood unrestricted as in the initial case. The curve is similar to the initial case except stretched in the x-direction which is essentially the extra time achieved by closing the door and restricting the progression of flooding. Next step is to simulate the effect of welding the door closed.

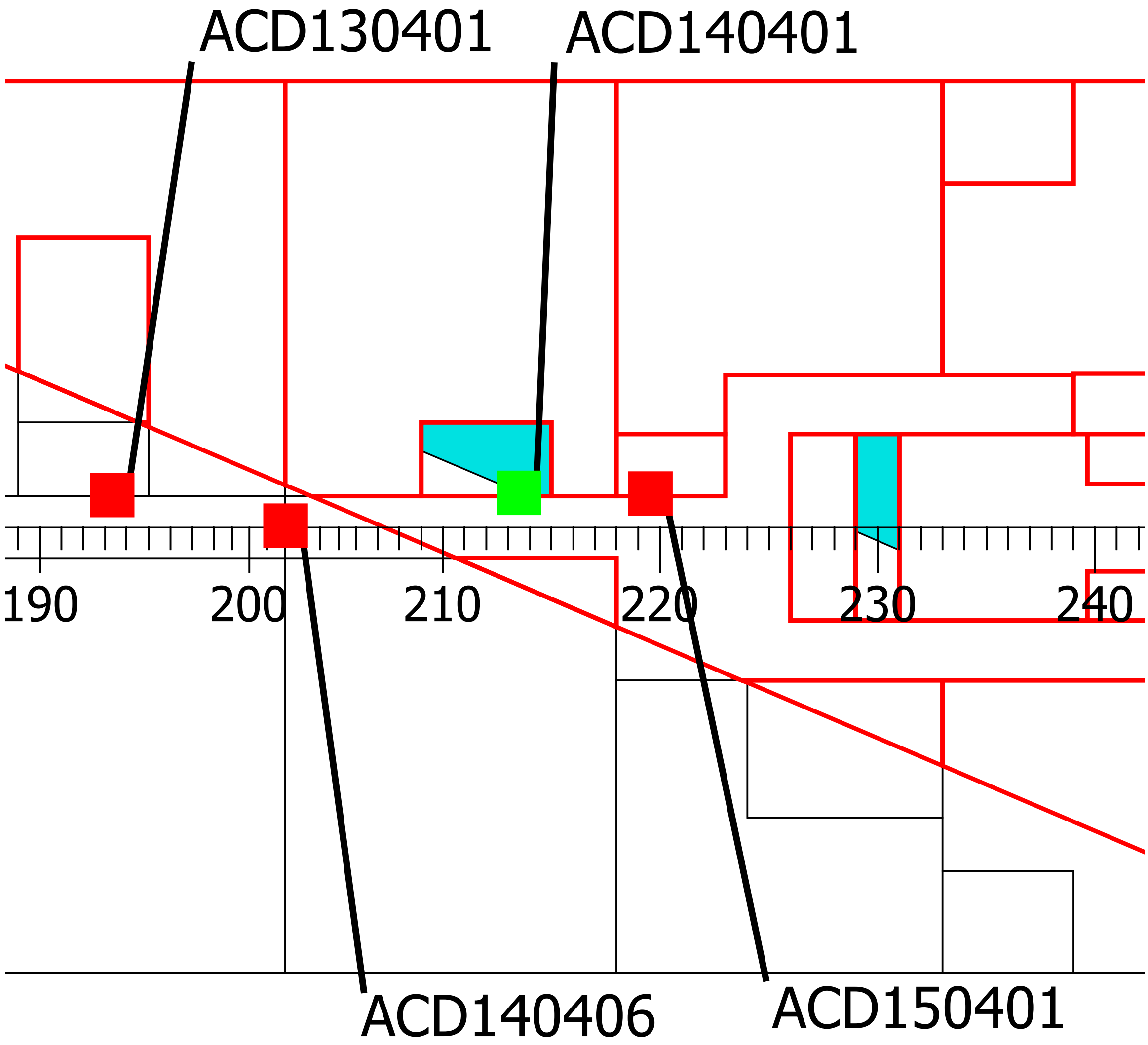


Figure 8.1 Closeup of the fire door statuses on the bulkhead deck in the SIDE 1 case at the moment when up-flooding to the bulkhead deck happens.

8.1.2 SIDE 2

Second case with the SIDE damage studies a situation where the fire door ACD140401 would be closed by welding. This is modelled by removing the door from the opening arrangement which makes the connection fully watertight. The goal in this simulation is to find out whether it is beneficial to consume time on welding doors closed or just simply close them. The situation is presented in Figure 8.2 where grey marks a fire door that is welded shut.

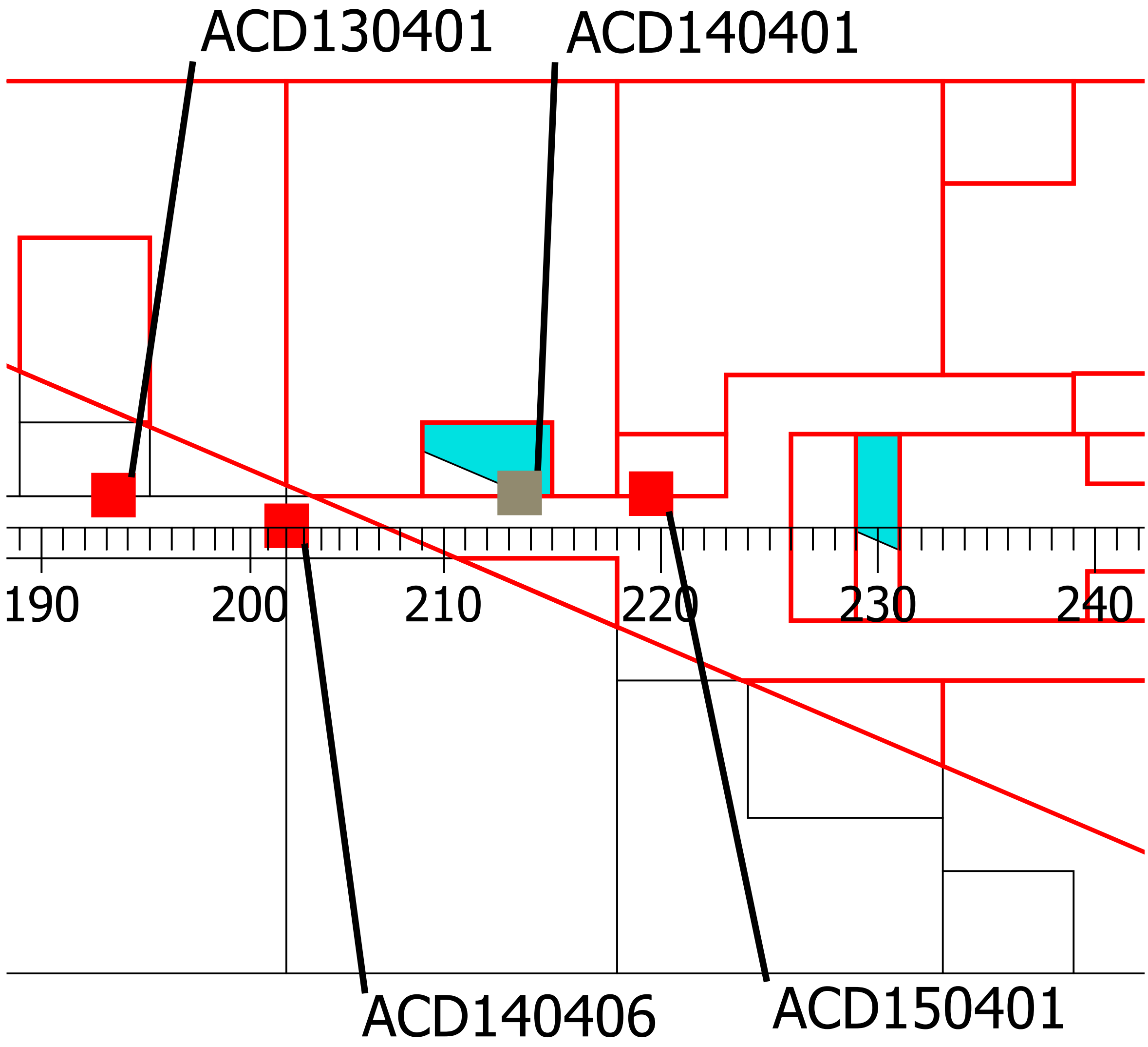


Figure 8.2 Closeup of the fire door statuses on the bulkhead deck in the SIDE 2 case at the moment when up-flooding to the bulkhead deck would happen through ACD140401.

With this setup, the simulation stops at 164 minutes after which the ship will capsize. Comparing to the previous SIDE 1 case, there is only a two minute improvement which is achieved by welding the door closed in this case. Evolution of heel in this case can be seen also in Figure 8.4. Simulation itself progresses a bit more successfully than with SIDE 1 in the end, with heel rising almost vertically over 30 degrees. Other than that, the heel evolution is very similar to SIDE 1 with the difference in times-to-capsize emerging in the end.

The result does not promote welding of doors, especially considering the effort and time the welding requires. In addition, the crew most probably is not able to weld the door closed before the water rises to the door 12 minutes after the impact. And though the crew was able to do that, water will rise to the deck from the adjacent staircase through opening ACD150401 regardless of the measures conducted on door ACD140401. Hence, the next simulation studies the effect of closing that door in addition to ACD140401.

8.1.3 SIDE 3

The last case studied with the SIDE damage has two fire doors closed, ACD140401 and ACD150401. This case is selected because after water floods through ACD140401 the next opening it will start flooding is ACD150401. If two first doors where water rises to the bulkhead deck are closed, there is a good chance for a major restriction of the bulkhead deck flooding. The situation is presented in Figure 8.3.

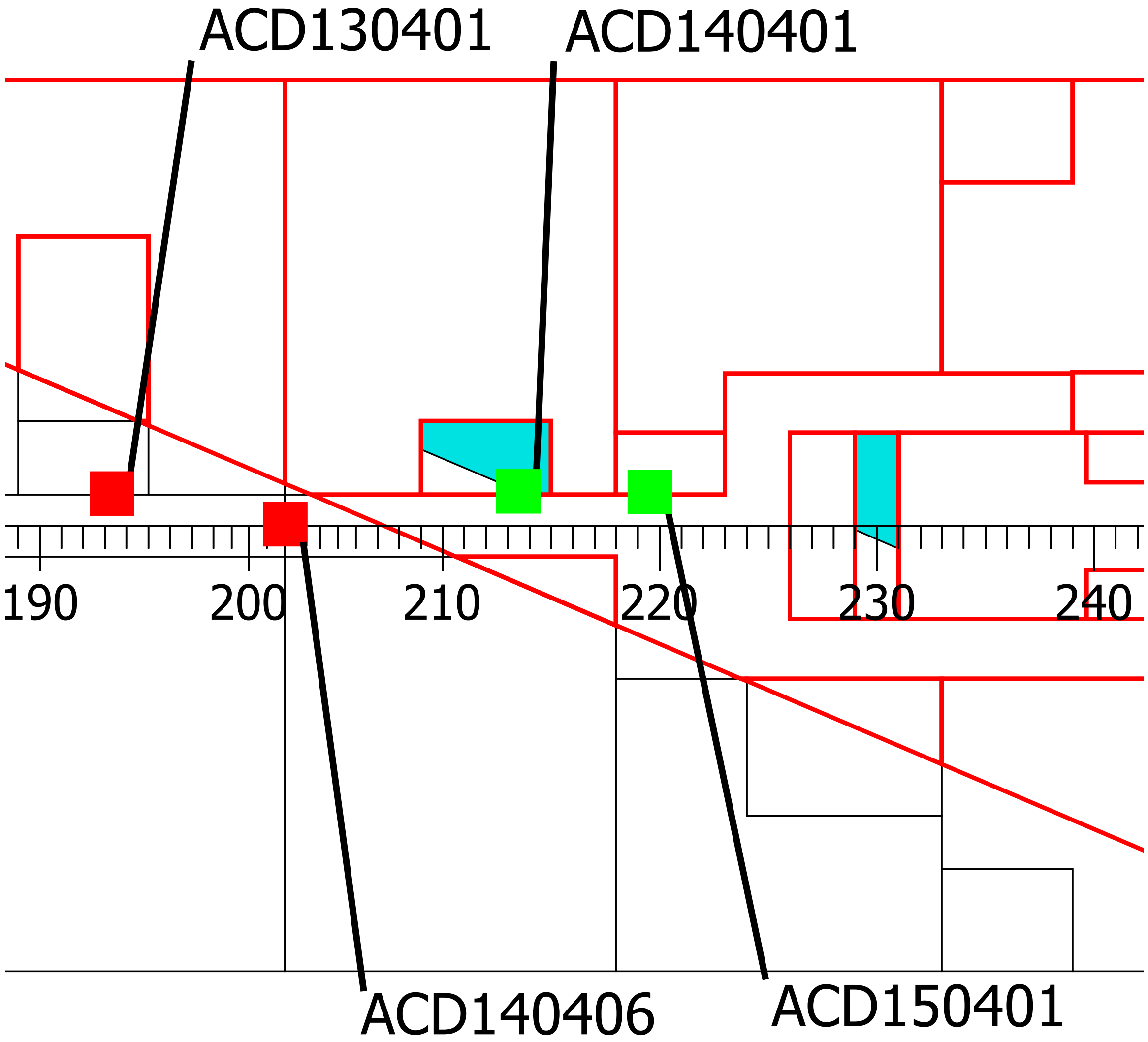


Figure 8.3 Closeup of the fire door statuses on the bulkhead deck in the SIDE 3 case at the moment when up-flooding to the bulkhead deck would happen through ACD140401.

With the case SIDE 3, the test ship will not sink even in five hours. About 20 minutes after the impact, the heeling angle of the ship is about half a degree and will continue to diminish slowly. This also is a very significant result. By closing two fire doors on the bulkhead deck, the ship will not sink with the SIDE damage. Evolution of the heel with SIDE 3 case is presented in Figure 8.4 as well. The heeling angle begins to differ from the previous cases after water reaches the closed doors in 12 minutes and the flooding scenario becomes practically stable after that.

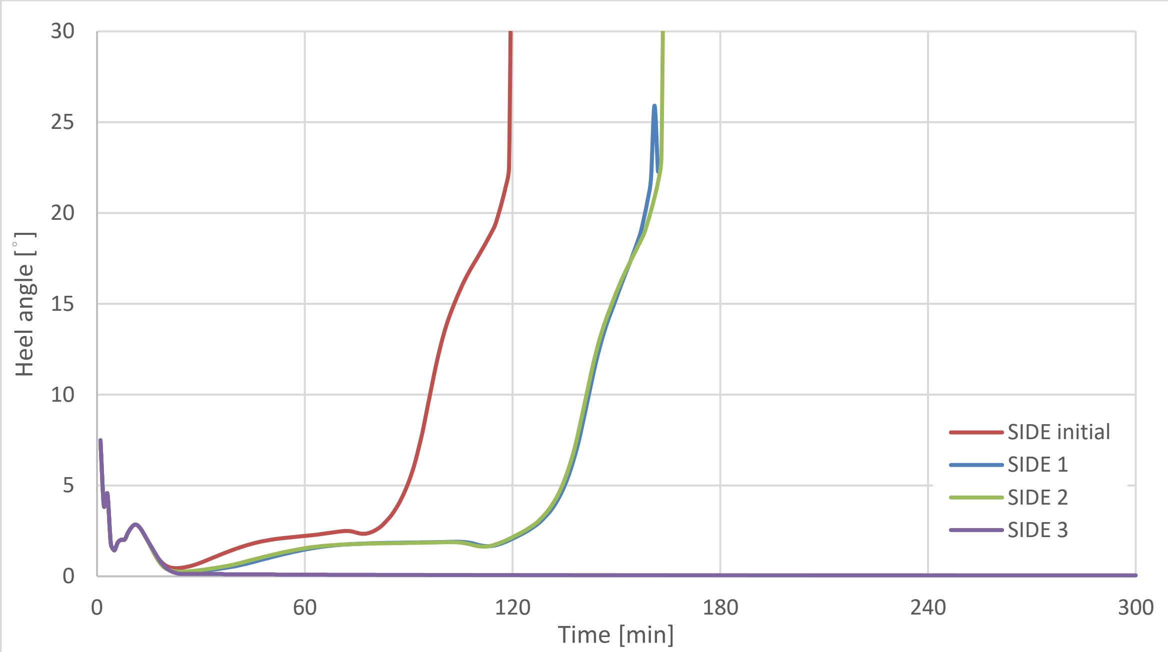


Figure 8.4 Heel angle evolution with the simulations SIDE, SIDE 1, SIDE 2 and SIDE 3.

8.1.4 BOTTOM 1

Water rose to the bulkhead deck already in two minutes after the BOTTOM damage with the initial opening arrangement. The first opening from which water leaked to the bulkhead deck was a closed fire door ACD150405 between a laundry chute and the service corridor. Since the situation evolves rapidly, there is no time to weld the door closed and it would not be justified as per the simulation SIDE 2. Thus the first countermeasure studied with the BOTTOM case is closing of fire doors ACD150401 and ACD140401 as closing of those doors proved to be effective in the simulation SIDE 3. They are in this case already below the waterline when water leaks from ACD150405 but the ingress water has not reached them yet. The situation can be seen in Figure 8.5.

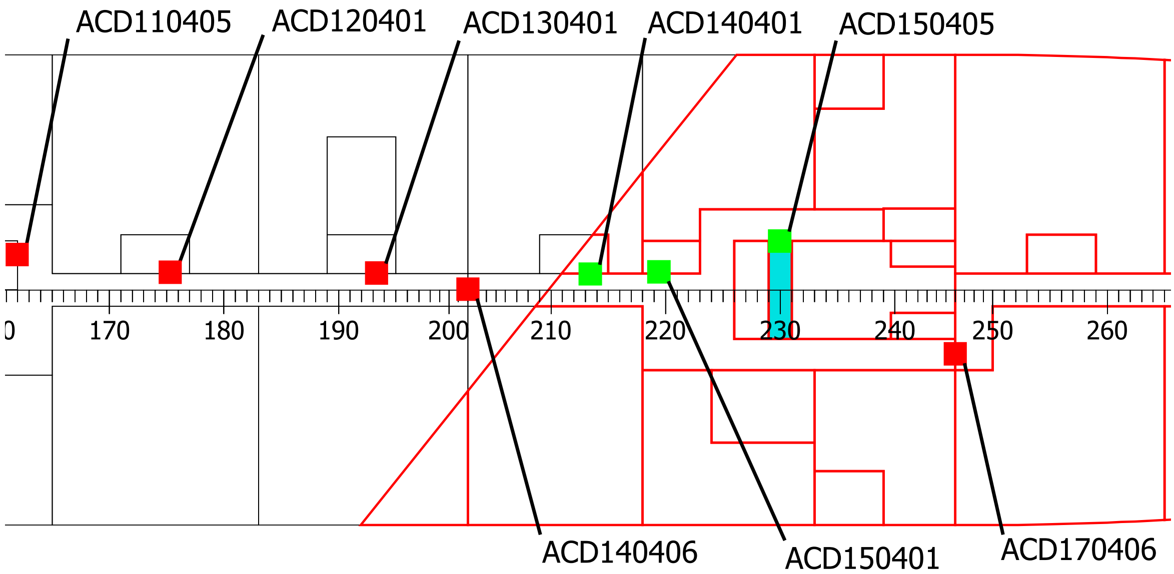


Figure 8.5 Closeup of the fire door statuses on the bulkhead deck in the BOTTOM 1 case at the moment when up-flooding to the bulkhead deck would happen through ACD150405.

With the BOTTOM 1 case the simulation stops and the ship sinks in 61 minutes. That is 26 minutes later than with the initial opening arrangement. The heel angle evolution can be seen from Figure 8.8. Negative heel means starboard heel in the figure. The heel angle does not increase as fast as in the initial case during the time from about 10 minutes to 40 minutes but after that the situation progresses similarly as in the reference BOTTOM case.

Though closing of only two doors almost doubles the time-to-capsize, it is still not enough for the evacuation of the ship. Thus, additional actions to mitigate progressive flooding on the bulkhead deck should be considered.

8.1.5 BOTTOM 2

As it was seen in the previous case, closing of two fire doors is not sufficient to provide enough time for evacuation in a damage case as massive as this. In this simulation, the effect of closing all fire doors between staircases and the service corridor above the damaged compartments is studied as was suggested already in Chapter 7.4. These openings consist of ACD110405, ACD120401, ACD130401 in addition to ACD140401 and ACD150401. The situation can be seen in Figure 8.6.

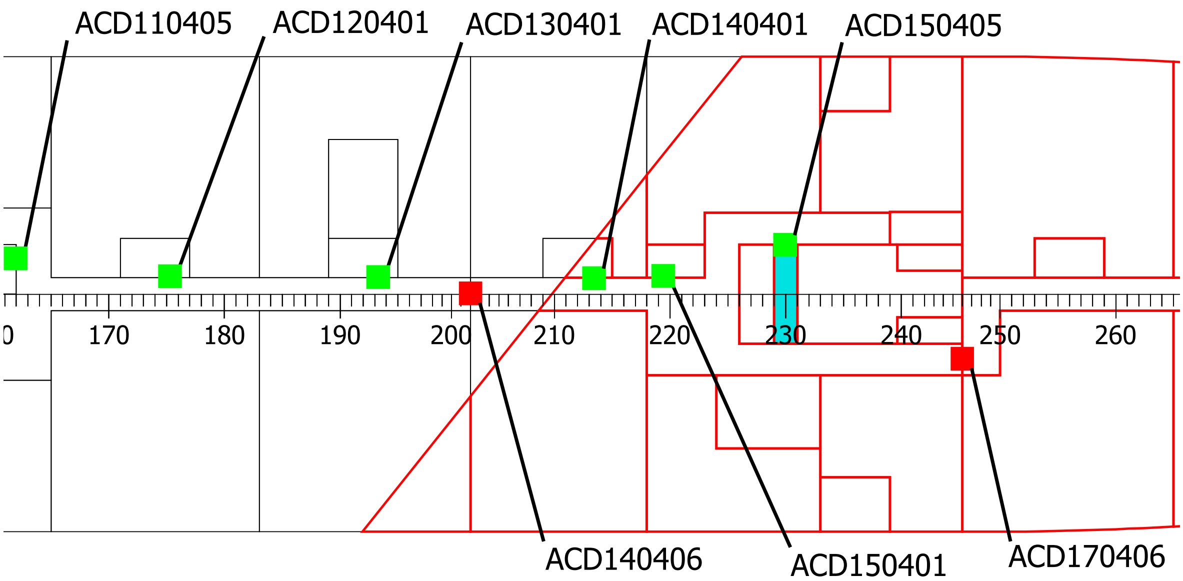


Figure 8.6 Closeup of the fire door statuses on the bulkhead deck in the BOTTOM 2 case at the moment when up-flooding to the bulkhead deck would happen through ACD150405.

With this door status arrangement, the simulation stops and the ship sinks in 193 minutes which is 3 hours and 13 minutes. This is an excellent result giving the crew 2 hours and 38 minutes more time to conduct the evacuation. The heel angle development can be seen in Figure 8.8. Closing all of the doors above the damaged compartments on the bulkhead deck between staircases leading to lower decks and the service corridor significantly restrains up-flooding of floodwater. This was of course assumable considering the small area ratio of closed fire doors.

As can be seen from Figure 8.6, there are still two fire doors on the service corridor which are left open. BOTTOM 3 simulation will concentrate on these.

8.1.6 BOTTOM 3

The last simulation with the BOTTOM damage focuses on the effect of closing double leaf fire doors along the service corridor. These doors have potential in preventing down-flooding to intact compartments by restricting the flow of floodwater along the service corridor. Although BOTTOM 2 resulted in a huge improvement from BOTTOM 1, BOTTOM 3 tries to find out if there still is any room for restricting progressive flooding on the bulkhead deck.

As it is in case of damages forward from the midship, the ship begins to trim by the bow as the flooding progresses. In this process, ingress water rising to a new deck flows always towards the bow. Thus the double leaf fire door ACD170406 has a vast potential in restricting this flow and should be shut. Also ACD140406 could restrict this flow but it does not directly prevent water from flooding to undamaged compartments. In this simulation, the door ACD170406 is closed in addition to the ones in BOTTOM 2. Door ACD140406 is left open to see the effect of closing only one service corridor double leaf door since it has not been simulated yet in this study. The situation can be seen in Figure 8.7.

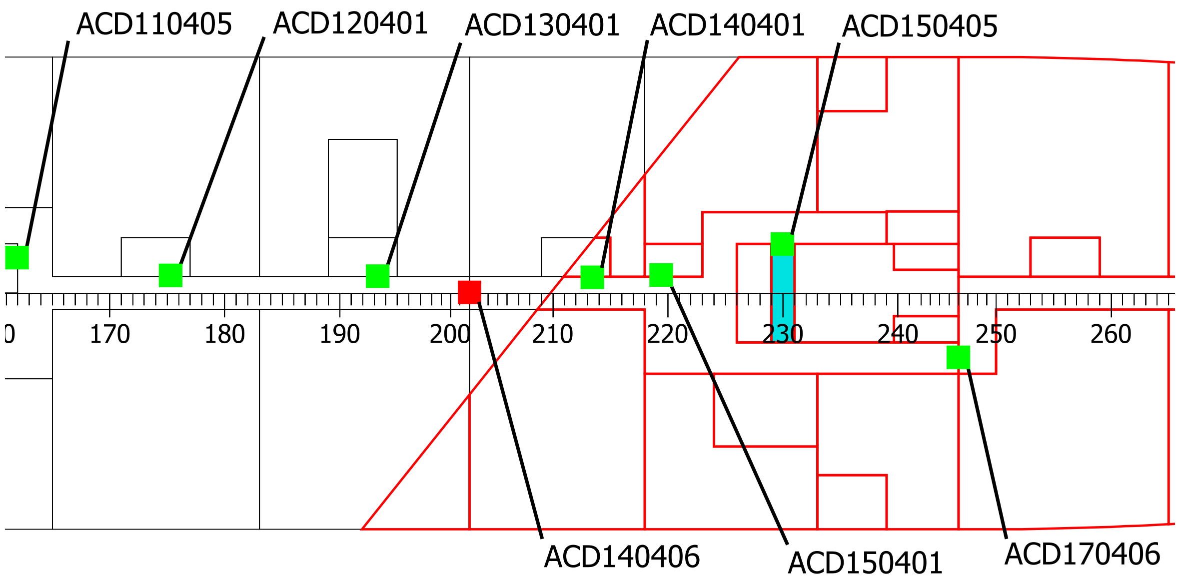


Figure 8.7 Closeup of the fire door statuses on the bulkhead deck in the BOTTOM 3 case at the moment when up-flooding to the bulkhead deck would happen through ACD150405.

With the case BOTTOM 3, the test ship does not sink even in five hours. The situation is not completely stable since the heel angle increases steadily but this development is rather slow as can be seen from Figure 8.8. By closing just six fire doors on the bulkhead deck increases the time-to-capsize at least by four and a half hours. This counteraction takes just a couple of minutes to carry out once the advice has been received from a DSS if the crew operates efficiently.

Though water is on the opening ACD150405 and the bulkhead deck in two minutes after the damage, it does not mean that the doors could not be closed. There is water flowing on the service corridor but it does not accumulate in the area where the doors should be closed immediately when there is water on the bulkhead deck.

Regardless of this, the advice from the DSS should come immediately when flooding sensors detect water in several compartments. There is no time for sophisticated simulations in a damage case as extensive as this but rather a simple instruction triggered by the signals from flooding sensors detecting water. The crew should also be trained to be able to operate effectively in a situation as severe as this. The communication could be handled e.g. by a public address system on the crew decks and the crew members on the bulkhead deck could close the doors immediately when informed to do so from the bridge. And should a false alarm occur, closing of fire doors does not cause any harm or danger.

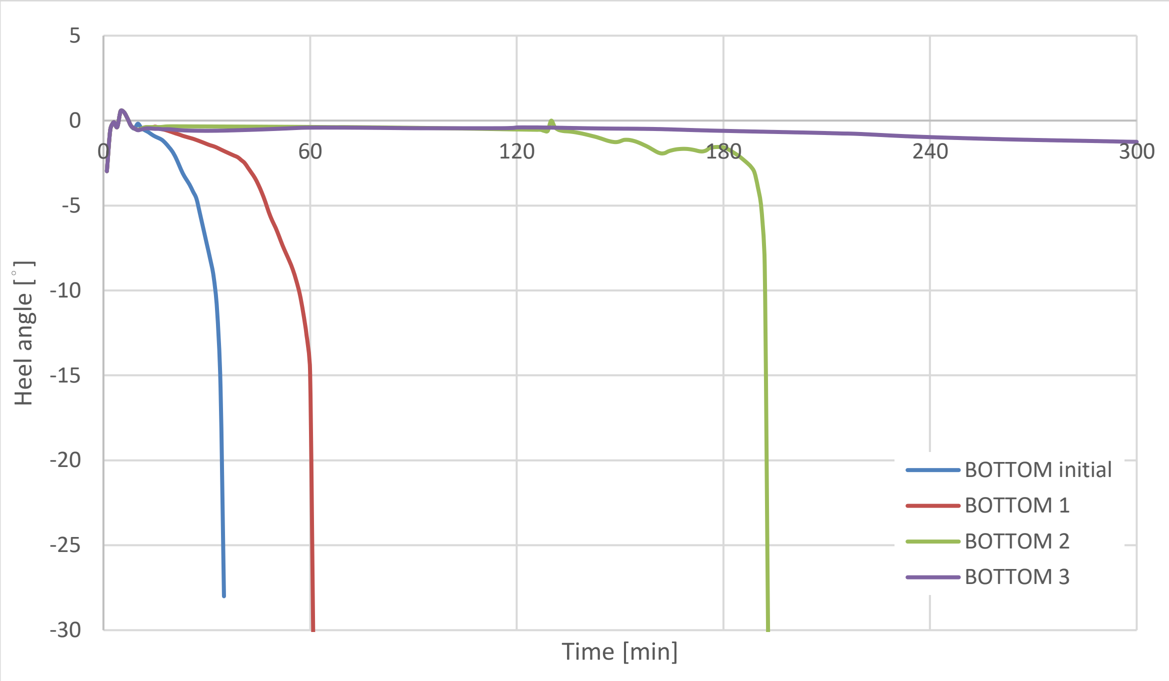


Figure 8.8 Heel angle evolution with the simulations BOTTOM, BOTTOM 1, BOTTOM 2 and BOTTOM 3.Negative values are for starboard heel.

8.1.7 SHOULDER 1

Water rose to the bulkhead deck already in four minutes from the fire door ACD180401 located between a staircase and the service corridor with the initial opening arrangement and the damage case SHOULDER. Thus the most natural countermeasure for the crew would be to close ACD180401 which is the simulation case SHOULDER 1. The situation is presented in Figure 8.9.

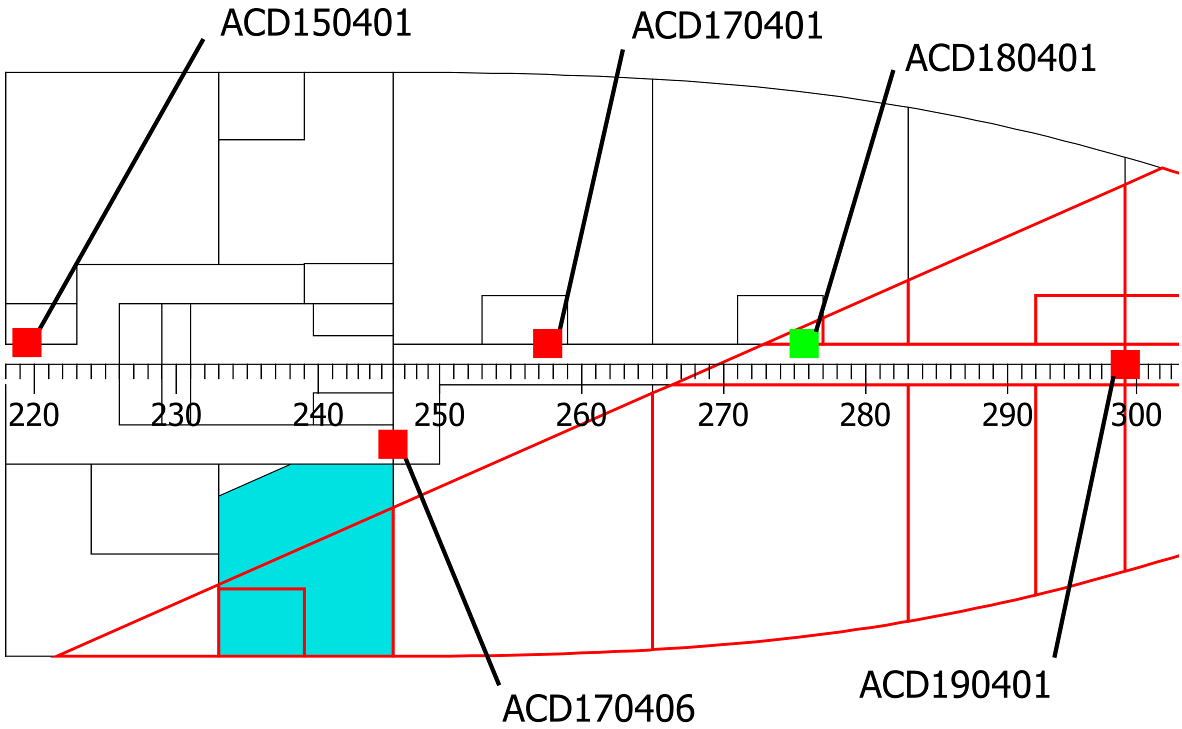


Figure 8.9 Closeup of the fire door statuses on the bulkhead deck in the SHOUDLER 1 case at the moment when up-flooding to the bulkhead deck would happen through ACD180401.

Closing of the door ACD180401 stabilizes the flooding scenario and the ship will not sink even in five hours as can be seen from Figure 8.10. Thus there is no need for the crew to close other doors. This simulation shows especially well the capability of a single fire door to stop progressive flooding almost completely. When water cannot rise to the bulkhead deck as freely as with an open ACD180401, water level does not reach ACD170401 or ACD150401 either which would accelerate the sinking process.

It should be noted that the flooding scenario proceeds as presented in Figure 8.10 if the crew is able to close ACD180401 in four minutes after the damage has occurred. If they are not able to operate that quickly but e.g. in 10 minutes the floodwater might reach ACD170401 and the ship might sink earlier. Thus the DSS should not give an instruction to close only one specific door but to be on the safe side and instruct to close all fire doors between staircases and the service corridor on the bulkhead deck above the damaged compartments as has been suggested before. The DSS should not give an over-optimistic solution but a robust instruction which has some safety margin and is “fool proof” since there is always variation between simulations and real life.

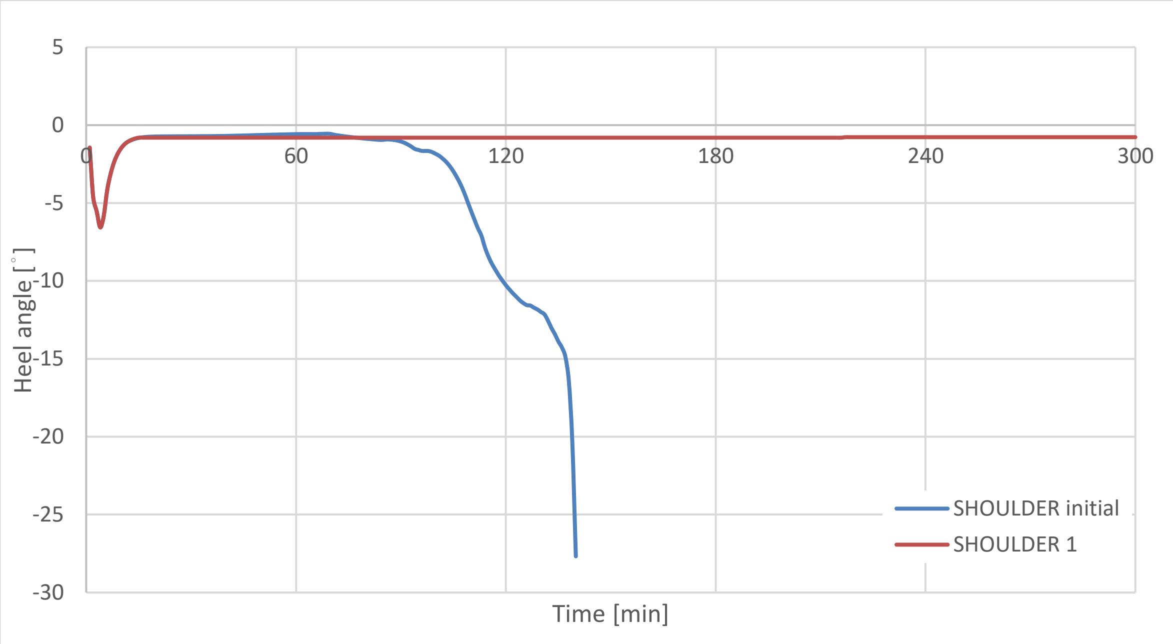


Figure 8.10 Heel angle evolution with the simulations SHOULDER and SHOULDER 1. Negative values are for starboard heel.

8.1.8 LOW SIDE 1

With the damage LOW SIDE water rose to the bulkhead deck in 9 minutes from opening ACD140401 which is an open fire door at frame 210 between a staircase and the service corridor. This is the same location as with the SIDE damage and again the first door that should be shut. Thus LOW SIDE 1 simulates the flooding with ACD140401 closed. The situation is presented in Figure 8.11.

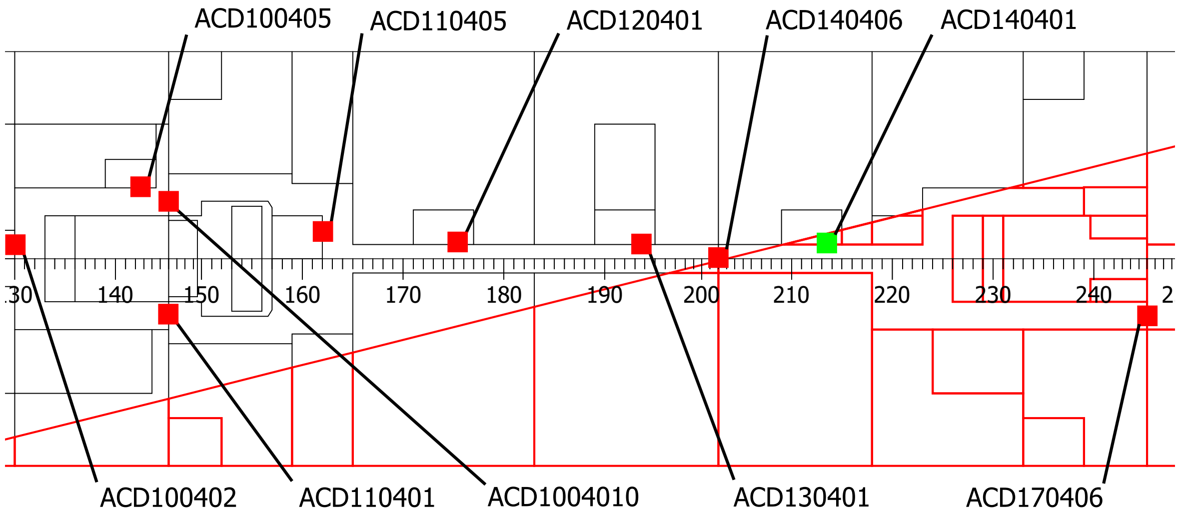


Figure 8.11 Closeup of the fire door statuses on the bulkhead deck in the LOW SIDE 1 case at the moment when up-flooding to the bulkhead deck would happen through ACD140401.

Closing only the door ACD140401 does not completely stabilize the flooding scenario but it prevents the ship from sinking during the studied five hour time window as can be seen in Figure 8.13. This verifies again the effect a single fire door can have on a flooding scenario. However, it might not be possible to close door in time as has been noted earlier. Thus the next simulation studies a case where ACD140401 is left open.

8.1.9 LOW SIDE 2

To find out the real effect of the fire door that first leaks water to the bulkhead deck on the flooding scenario, a simulation should be ran where that door is left open. LOW SIDE 2 represents such a case. In this simulation, all fire doors on the bulkhead deck above the damaged compartments are closed apart from ACD140401 which is the door that first leaks water on the service corridor. ACD170406 which is a double leaf door located forward from ACD140401 capable of preventing progressive flooding towards the bow is left open as well but it is not located above the damaged compartments. The situation can be seen in Figure 8.12. There is also a hinged fire door on frame 220 but it is not marked to Figure 8.12 since it is not located over a damaged compartment and is not a source of ingress water on the service corridor.

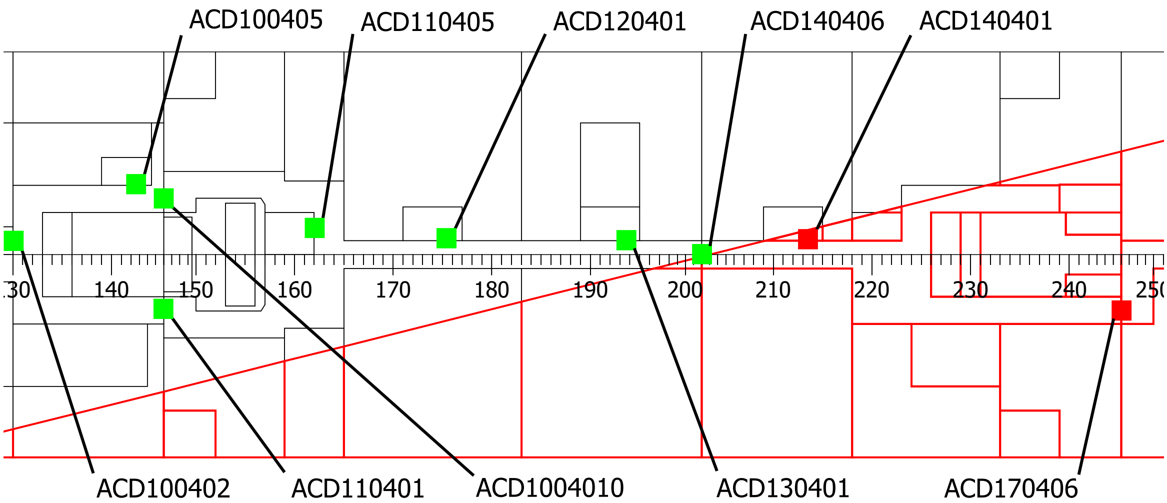


Figure 8.12 Closeup of the fire door statuses on the bulkhead deck in the LOW SIDE 2 case at the moment when up-flooding to the bulkhead deck would happen through ACD140401.

With this door configuration, the simulation stops and the ship sinks in 258 minutes which is 4 hours and 18 minutes. The heel angle development can be seen in Figure 8.13. The result shows that the test ship cannot be saved from sinking within five hours from the damage if the door where water first floods to the bulkhead deck is not closed. Closing of all the other doors that are located above the damaged compartments and connect the bulkhead deck to lower decks that are flooded via staircases does not provide as safe solution as closing ACD140401 which is the origin of water on the bulkhead deck. This is a significant result highlighting the importance of closing the door which is the major source of floodwater on the bulkhead deck.

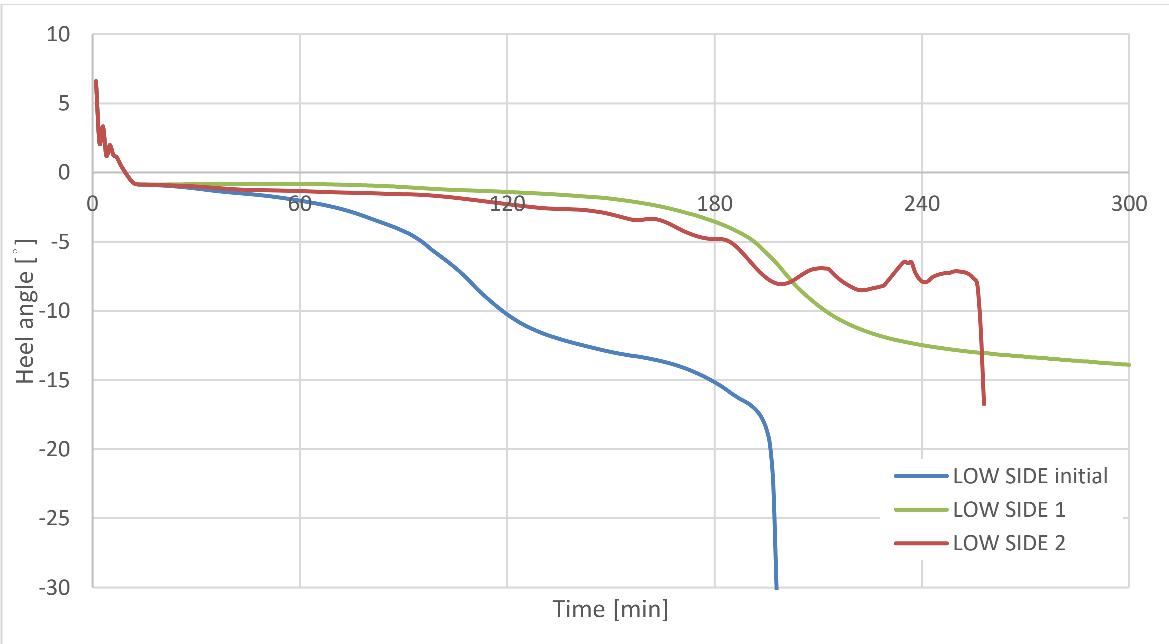


Figure 8.13 Heel angle evolution with the simulations LOW SIDE, LOW SIDE 1 and LOW SIDE 2. Negative values are for starboard heel.

As was seen in this, BOTTOM and SHOULDER cases, water rises to the bulkhead deck from the foremost fire door between a staircase and the service corridor above the damaged compartments. With the SIDE damage it rose from the second foremost door. Thus it can be concluded that in flooding scenarios where an extensive damage is located forward from the midship, the foremost fire doors on the bulkhead deck between staircases and the service corridor have the biggest role in controlling the flooding. Hence the focus of closing fire doors as a countermeasure should be put to these doors especially.

8.2 Logic for suggesting countermeasures

The simulations showed the potential of closing fire doors as a countermeasure to prevent progressive flooding on board a cruise ship. Now a simple logic needs to be formed for NAPA EC to instruct closing of the correct doors.

As it was suggested in the BOTTOM 3 case, the advice to close certain fire doors should come immediately when the flooding sensors detect water without the need for accurate flooding prediction calculations. This means that fire doors on the bulkhead deck between staircases and the service corridor should be linked in the system to rooms below them equipped with flooding sensors from where up-flooding is possible. This way if water is detected in room from where it can rise to the bulkhead deck via a staircase, NAPA EC can immediately suggest to close the corresponding fire door on the bulkhead deck. This should be done also for the double leaf doors along the service corridor with the exception that they should be linked to several adjacent compartments because they do not directly prevent up-flooding in a damaged WT-compartment but the spreading of water on the bulkhead deck. Double leaf fire doors on the service corridor can restrict progressive flooding though the WT-compartment they are located in is not damaged. Hence, double leaf doors should be linked to all WT-compartments either in the foreship or aftship based on their own location. For example, if the damage is in the foreship, all double leaf fire doors along the service corridor forward from the midship should be closed because water flows towards the bow when it reaches the service corridor.

The LOW SIDE 2 case proved the importance of closing the door that is the source of water on the bulkhead deck. Thus the doors should be prioritized based on the location of the damage and the location of the doors. If damage is in the foreship the foremost door should be closed first and if the breach is located in the aftship, the aftmost doors should be prioritized. NAPA EC can present a list of the doors to be closed sorted based on their priority.

Though the simulations focused on the effect of closing of fire doors on the flooding scenario, the role of watertight doors is still the most important factor affecting on the outcome of a flooding case. Most of them should be closed during navigation according to current regulations and closing of them in a damage situation should be obvious for the crew. But as was seen in the reviewed accidents, this has not always been the case. Though NAPA EC monitors the vulnerability level of the ship constantly highlighting the danger of open watertight doors, an instruction to close all watertight doors should be given by the system if ingress water is detected by flooding sensors.

Also the instruction to discharge swimming pools on top decks should be given if ingress water is detected by the flooding sensors. The effect of it was not simulated in the cases but it can be confirmed to be positive from stability point of view. This is because discharging the pools on the top decks lowers the center of gravity of the ship and reduces the free surface moment originating from the pools. This increases the metacentric height of the ship resulting in better stability.

Table 8.1 summarizes the countermeasure advice that should be given to the crew of a damaged passenger ship based on the analysis conducted in this thesis.

Table 8.1 Summary of the suggested countermeasure advice.

<table>
<tr><td colspan="2">Water detected by flooding sensors
- Close all watertight doors
- Discharge swimming pools on top decks</td></tr>
<tr><td>Damage in aftship</td><td>Damage in foreship</td></tr>
<tr><td>- Close fire doors above the damaged compartments on the bulkhead deck between staircases and the service corridor prioritizing the AFTMOST doors

- Close double leaf fire doors on the service corridor in the AFTSHIP</td><td>- Close fire doors above the damaged compartments on the bulkhead deck between staircases and the service corridor prioritizing the FOREMOST doors

- Close double leaf fire doors on the service corridor in the FORESHIP</td></tr>
</table>

Now as the method for identifying the closed doors has been specified, a logic about the decision making process of NAPA EC suggesting countermeasures can be formed. The process is presented in Figure 8.14. When flooding sensors detect water, the instruction to close all watertight doors and discharge swimming pools on top decks can be given without any other information. Based on flooding sensor data, NAPA EC identifies the WT-compartments affected with the fire doors between staircases and the service corridor linked to them and calculates whether the damage is in the aft or foreship by calculating average of the affected WT-compartment numbers and deducting the average of all WT-compartment numbers from it. If the result is positive, the damage is in the foreship, if negative the damage is in the aftship and the system can identify also the relevant double leaf doors along the service corridor. The damage location determines the order in which the doors to be closed are listed. Hinged doors between staircases and the service corridor above the damaged compartments are always presented before double leaf doors along the service corridor. If the result of the damage location calculation is zero, NAPA EC suggests to close all of the double leaf fire doors along the service corridor. The order of the doors between staircases and the service corridor is not that important in such a case and they can be sorted e.g. starting from the foremost.

Water detected by a flooding sensor ↓	Example: case **BOTTOM**
”Close all watertight doors” ”Discharge swimming pools on top decks” ↓	”Close all watertight doors” ”Discharge swimming pools on top decks”
Identify the affected rooms from where up-flooding to the bulkhead deck is possible ↓	Rooms on deck 1 in WT-compartments 11-15
Identify the fire doors between staircases and the service corridor linked to the breached rooms ↓	ACD110405, ACD120401, ACD130401, ACD140401, ACD150401, ACD150405
Calculate location of the damage taking into account all breached WT-compartments ↓	$D = \frac{11+12+13+14+15+16+17+18+19}{9} - \frac{\sum_{i=1}^{22} i}{22}$ $= 3.5 > 0$ -> damage is in the foreship *
Identify relevant double leaf fire doors along the service corridor based on damage location ↓	ACD140406, ACD170406, ACD190406
Sort out all doors by priority ↓	”Close fire doors: ACD150405 ACD150401 ACD140401 ACD130401 ACD120401 ACD110405 ACD140406 ACD170406 ACD190406”
”Close fire doors 1, 2, 3...”	

*
Calculate mean value for affected compartment numbers and compare to the mean value of all compartments:

$D = average(affected\ WT\ compartments) - average\ (all\ WT\ compartments)$

If $D < 0$ damage in aftship -> highest priority with aftmost doors, double leaf doors in aftship to be closed
If $D = 0$ damage in midship -> highest priority with foremost doors, all double leaf doors to be closed
If $D > 0$ damage in foreship -> hihgest priority with foremost doors, double leaf doors in foreship to be closed

Figure 8.14 A suggestion for a logic to NAPA EC for giving countermeasure advice.

The logic suggested here does not require any input to NAPA EC from the user of the system. It is based on flooding detection from automatic sensors. This approach is selected to have as simple solution for the countermeasure advice process as possible and to direct the crew's effort to the actual actions to mitigate the effects of the damage suffered.

Figure 8.14 displays also an example for using the logic in the BOTTOM case. Water is detected in watertight compartments 11-19 but up-flooding is possible only from rooms in 11-15 because of the location of damage. Breached rooms in WT-compartments 16-19 do not have openings to any staircase or escape hatch which would enable up-flooding. Fire doors on the bulkhead deck between a staircase and the service corridor are linked to rooms with flooding sensors below them and once such sensor detects water, NAPA EC can identify the correct door to be closed on the bulkhead deck to prevent up-flooding to the bulkhead deck. In this case doors ACD110405, ACD120401, ACD130401, ACD140401, ACD150401 and ACD150405 would be linked to the breached rooms. After this, a simple calculation is conducted to find out that the damage is in the foreship which determines the double leaf fire doors on the service corridor to be closed: ACD140406, ACD170406 and ACD190406. Based on the damage location, the fire doors are sorted so that the foremost is first on the list of the doors to be closed since that is the location where water rises to the bulkhead deck already in two minutes after the damage. The doors to be closed are highlighted also in the deck plans of the GUI of NAPA EC.

8.3 Prototype of the graphical user interface

When ingress water is detected by the flooding sensors, NAPA EC switches to the survivability calculation mode which can be seen in Figure 8.15. Left hand side of the screen includes the Vessel TRIAGE color coded survivability gauge, basic details of the floating position and information about the rooms where floodwater has been detected together with the volume and flooding rate of the ingress water. The current flooding state is visualized in the deck plans on the right hand side of the GUI.

New features added to the GUI of NAPA EC based on the results obtained in this thesis consists of the countermeasure advice visible in Figure 8.15 in the red box instructing to close all watertight doors, specific fire doors and to discharge swimming pools on top decks. The fire doors to be closed are visualized with red squares and warning triangles in the deck plans found from the right side of the countermeasure advice box.

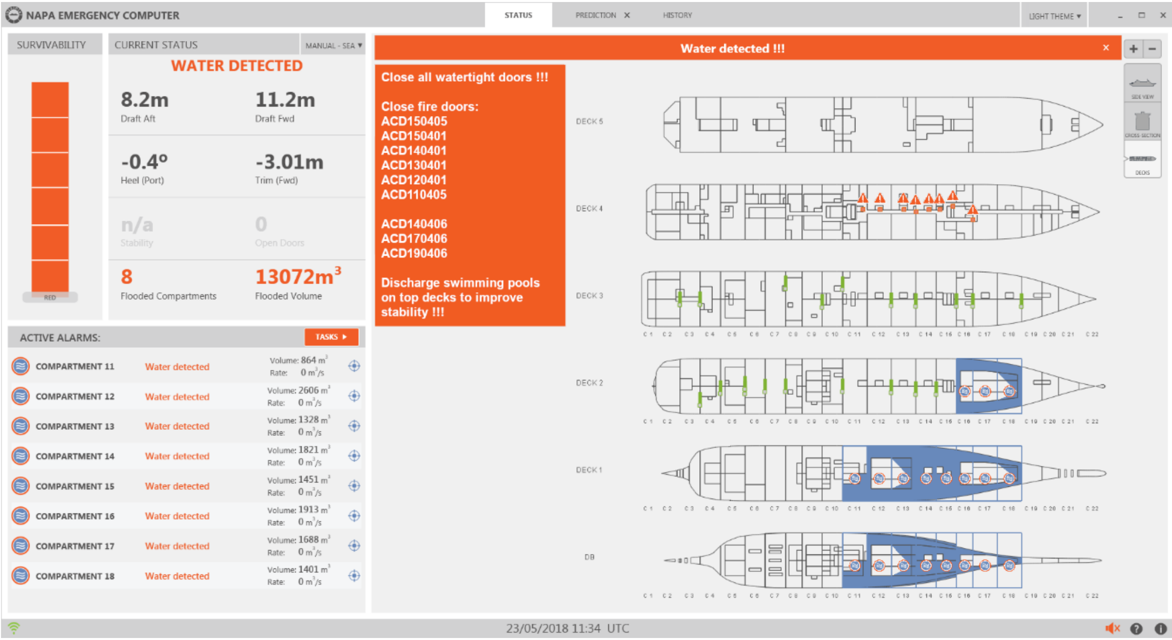


Figure 8.15 GUI of NAPA EC updated with a countermeasure advice.

Figure 8.16 shows a zoomed view of the deck plans identifying the fire doors to be closed. Once mouse is hovered over a fire door, a dialog opens where additional information about the door can be stored, e.g. a picture of the door to help the crew in locating the door.

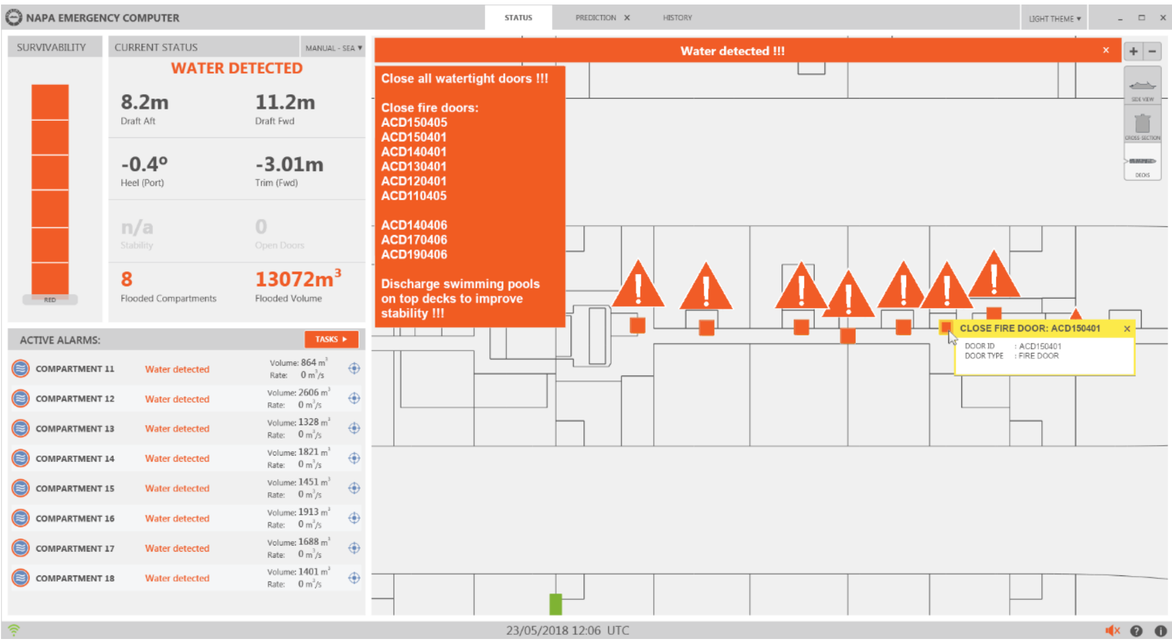


Figure 8.16 Closeup of the fire doors to be closed.

9 Conclusions

Safety on board passenger ships has been paid a lot of attention to during the years. Ever increasing design rules might have already reached a point where it is not anymore feasible to develop stricter ones. This calls for raising the safety level of passenger ships with operational measures e.g. by a comprehensive decision support system advising the crew in a flooding situation.

Several computerized DSSs have been developed during the last ten years or so both for naval and passenger ships to help the crews to react quicker and more effectively to a flooding situation. This is essentially improving the safety and survivability of the ship through operational measures.

Most of the defense industry targeted DSSs focus on counter-ballasting options to improve the stability of a damaged ship with some also taking maneuverability of the vessel into account. The ballasting advice is justified in naval ships with denser subdivision and relatively bigger ballasting tanks compared to passenger ships. The importance of maneuverability of a naval ship originates from the need to be able to battle also when damaged. Other areas focused on in naval ship DSSs include monitoring of the functionality of all the systems on board and a virtual environment approach to help the crew to visualize the current situation and system effectively.

There are not that many DSSs developed for passenger ships than for naval ships. The focus areas of passenger ship DSSs include risk assessment of an intact ship or also so called vulnerability, flooding prediction and survivability assessment of a damaged ship. The most widespread system within the industry combining all these features is NAPA Emergency Computer developed by Napa Ltd. It can be found on board most of the biggest cruise ship newbuildings. However, there is not yet a DSS aimed for passenger ships, which would combine vulnerability and survivability assessments, accurate flooding prediction and countermeasure advice to form a holistic system advising the crew in a stressful emergency situation. The main goal of this thesis was to constitute one.

To be able to highlight the most effective countermeasures for the user of the DSS, different passenger ship flooding accidents and scientific literature was reviewed to find out the most feasible countermeasures for a cruise ship. Preventing progressive flooding proved to be the most promising counteraction the crew should focus on instead of e.g. ballasting or maneuvering. Closing of watertight doors is the most effective way to prevent the ingress water from spreading but it is self-evident and did not need to be studied in detail. However, that does not prevent up-flooding via e.g. staircases. Closing of non-watertight doors such as fire doors leading to staircases is capable of preventing up-flooding e.g. to the bulkhead deck. Thus, the effect of closing fire doors on the flooding case was selected to be inspected in more detail through flooding simulations.

The flooding simulations were conducted in NAPA ship design software with a model of a 125,000 GT modern cruise ship. All watertight doors were closed and the non-watertight door statuses were modified to represent reality as accurately as possible taking into account the operating crew. A loading condition with the ship's maximum draft was formed and realistic damage cases were created to represent probable grounding damages a cruise ship can encounter and which eventually would lead to sinking.

The simulations showed that closing of hinged fire doors on the bulkhead deck above the damaged compartments between staircases and the service corridor can significantly restrict up-flooding to the bulkhead deck thus increasing the time-to-capsize. In the SHOULDER 1 case, closing of just one fire door increased the time-to-capsize from 2 hours 20 minutes to over 5 hours. It became clear during the simulations that the fire door from where water first rises to the bulkhead deck has the biggest potential in restricting bulkhead deck flooding together with its neighboring fire doors above the damaged compartments between staircases and the service corridor. Thus, in case of damage to the foreship the foremost fire doors above the damaged compartments between staircases and the service corridor should be shut first with the priority decreasing towards aftship, and vice versa in case of damage to the aftship. The positive effect of closing the double leaf fire doors along the service corridor to prevent undamaged compartments to be down-flooded was also found in the simulations. It was also noted in the SIDE 2 case that welding of fire doors is not feasible.

In the studied damage cases, water was on the bulkhead deck in less than 12 minutes which called for swift operation of the DSS to suggest any countermeasures for the crew. This pointed out that the DSS does not have time for sophisticated simulations but should instead immediately give advice on the countermeasures when the flooding sensors detect water. A simple logic for suggesting closing of all watertight doors, the relevant fire doors and discharging swimming pools was formed. The relevant fire doors to be closed were obtained from the simulation conclusions. As a summary, the fire doors on the bulkhead deck above the damaged compartments between staircases and the service corridor should be shut immediately when ingress water is detected with highest priority on the foremost doors in case of damage to the foreship and aftmost doors in case of damage to the aftship. Also the double leaf fire-doors along the service corridor should be closed also depending on the location of the damage.

Finally when the simple logic for suggesting countermeasures was formed, a prototype GUI of NAPA EC suggesting counteractions for the user of the system was sketched. The system used to be rather passive without any direct advice messages to the user but just presenting the current situation and the flooding prediction. Now the prototype GUI of NAPA EC advices to close all watertight doors, relevant fire doors and to discharge swimming pools if the flooding sensors detect water. This accelerates the decision making progress. And if the advice is wrong for some reason, e.g. malfunction of the flooding sensors, the countermeasures do not cause any danger to the safety of the ship unlike e.g. faulty ballasting advice leading to worsened stability.

Since the role of fire doors on restricting progressive flooding was found significant in this thesis, there is plenty of work to be conducted in the future to find out the full potential of the countermeasure. This thesis focused only on extensive damages leading to sinking but the capability of fire doors to improve damage stability also in smaller damage cases where the water doesn't rise to the bulkhead deck should be studied. In such cases, the ingress water progresses slowly inside the ship and there is more time and options for the doors to be closed. This creates a demand for utilizing the flooding prediction to solve the route of floodwater inside the ship and highlight the individual fire doors to be closed along that route.

Since closing of fire doors aims at prolonging the time-to-capsize hence buying more time for evacuation of passengers, the effect of the closed fire doors itself on the evacuation time could be studied in the future and taken into account in the process of highlighting the most feasible doors to be closed. It might be that in some damage case a fire door necessary to be open for evacuation should be closed to restrict the flow of floodwater inside the ship. In such case an alternative door to be closed should be found. Therefore, future work on refining the countermeasure advice should take evacuation routes into account.

The logic used in this thesis for determining the location of the damage, whether in aft- or foreship, is rather simple and doesn't take into account the volumes of the damaged compartments which would be needed to predict the trim evolution of the ship and direction of water flow inside the ship always correctly. This has effect on the closing order of the doors on the bulkhead deck. An alternative method for this could be studied in future work, e.g. based on actual trim evolution from draft sensor readings.

There is room for future work also in the user interface of the countermeasure prototype of NAPA EC to ensure the most intuitive and effective use of the system. The importance of a good user interface is emphasized in a decision support system aimed at accelerating the decision making process during a stressful event with the potential of saving human lives.

Future work on the subject will hopefully bring more light to the feasibility of closing fire doors as a countermeasure to combat a flooding scenario. If the potential of this countermeasure is realized in large scale, it will have permanent effect on what actions the crew should take if a passenger ship encounters a flooding damage.

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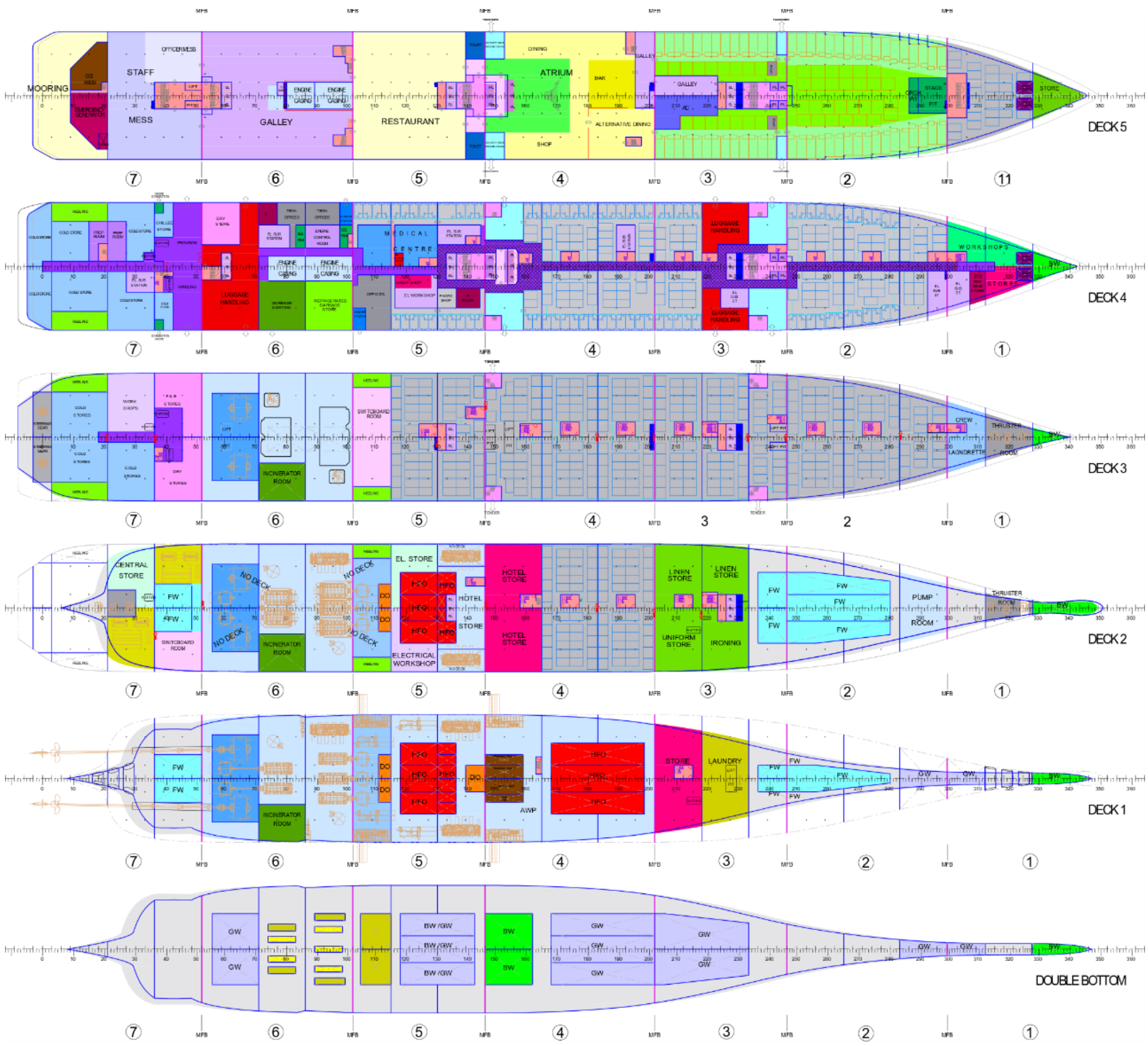
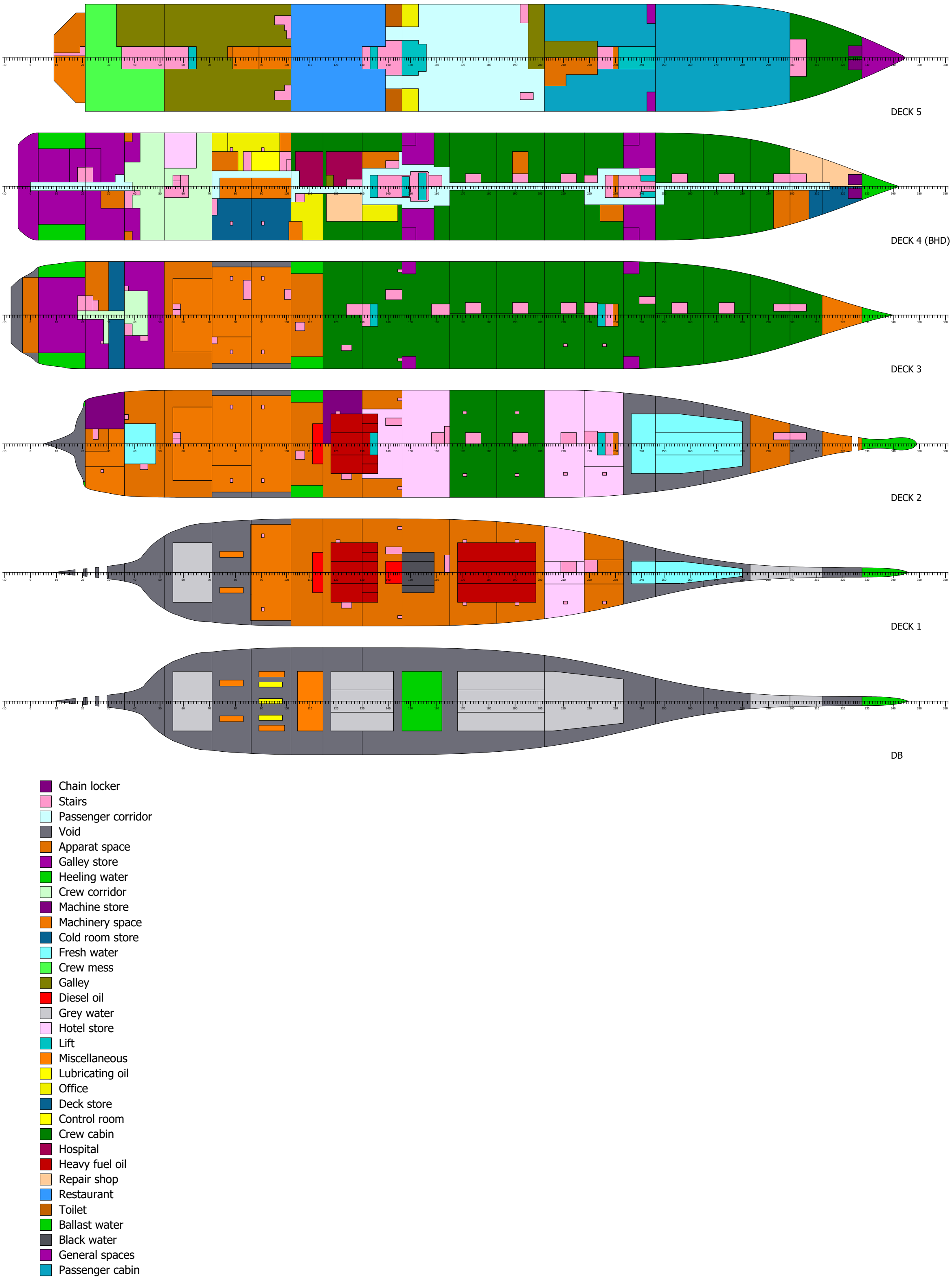
List of appendices

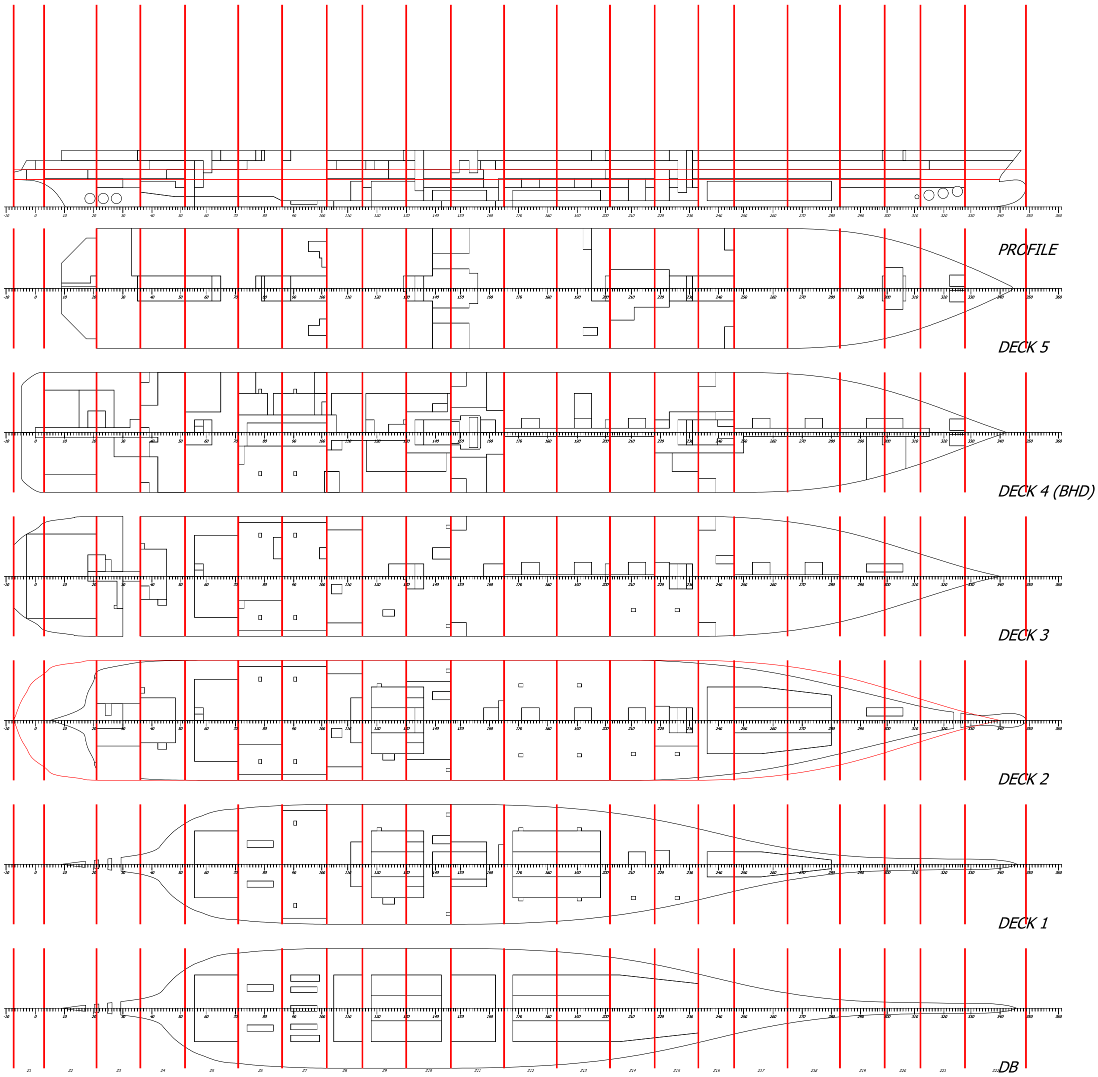
Appendix 1. Original room arrangement



Appendix 2. Modified room arrangement used in the model

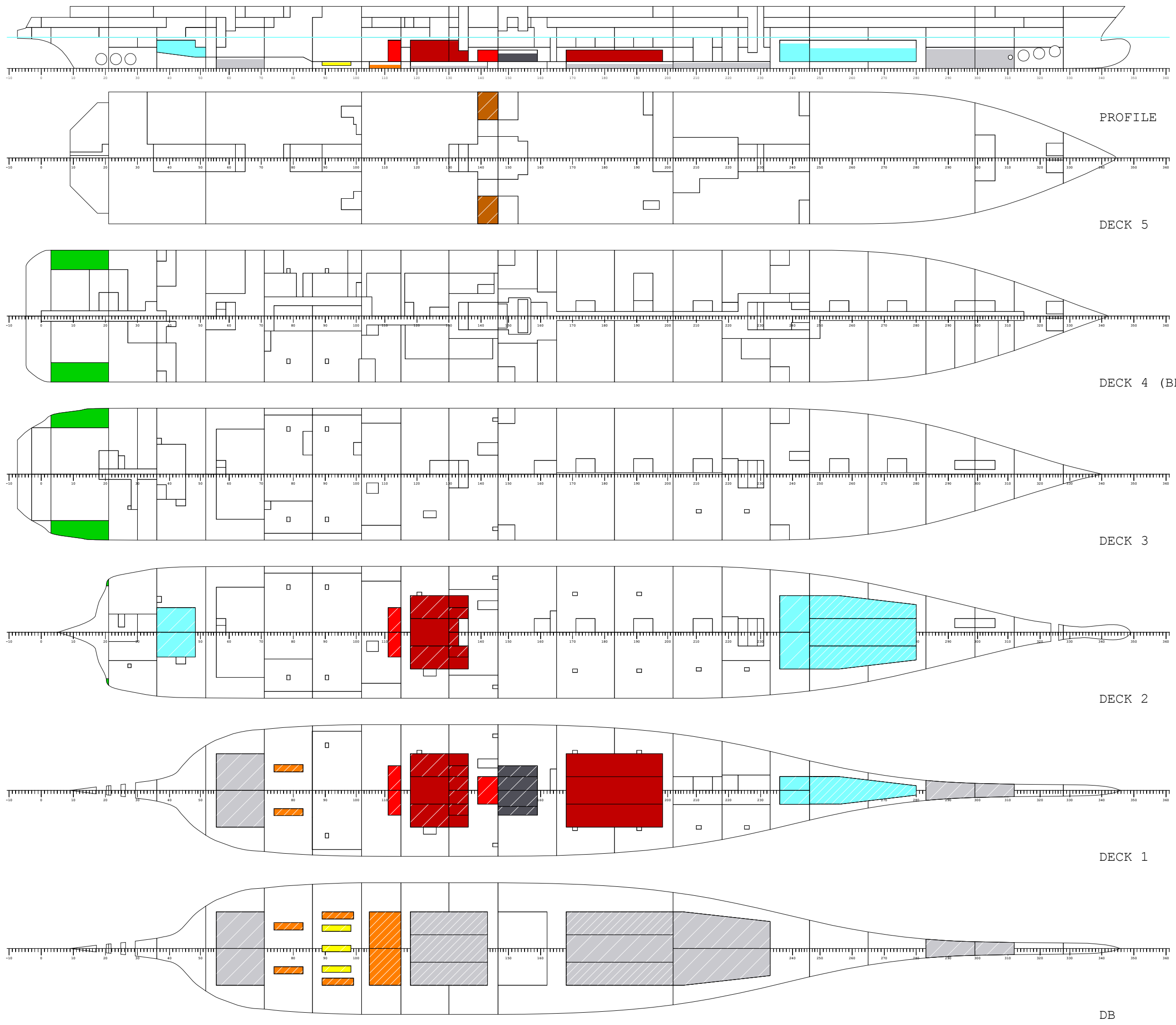


Appendix 3. Watertight subdivision of the test ship



Appendix 4. Loading condition

LOADING CONDITION: LOAD100 -



LOAD	MASS t	XM m	YM m	ZM m	FRSM tm
Deadweight	13685.3	140.40	-0.01	7.23	22066.94

Lightweight	56835.7	134.42	0.00	19.98
Deadweight	13685.3	140.40	-0.01	7.23
Total weight	70521.0	135.58	0.00	17.51

FLOATING POSITION

Draught moulded	8.799	m	KM	20.55	m
Trim	-0.002	m	KG	17.51	m
Heel, PS=+	-0.1	deg			
TA	8.800	m	GM0	3.04	m
TF	8.799	m	GMCORR	-0.31	m
Trimming moment	-339	tonm	GM	2.73	m

Stability Criteria

RCR	TEXT	REQ	ATTV	UNIT	STAT
AREA20	Area under GZ curve .	0.065	0.165	mrad	OK
AREA40	Area under GZ curve .	0.090	0.587	mrad	OK
AREA3040	Area under GZ curve .	0.030	0.220	mrad	OK
MAXGZ20	Max. GZ at an angle .	20.000	32.192	deg	OK
GZ0.2	Max GZ > 0.2	0.200	1.309	m	OK
MAXHEELPASS	Max. heel due to cro.	10.000	1.840	deg	OK
MAXHEELTURN	Max. heel due to tur.	10.000	2.809	deg	OK

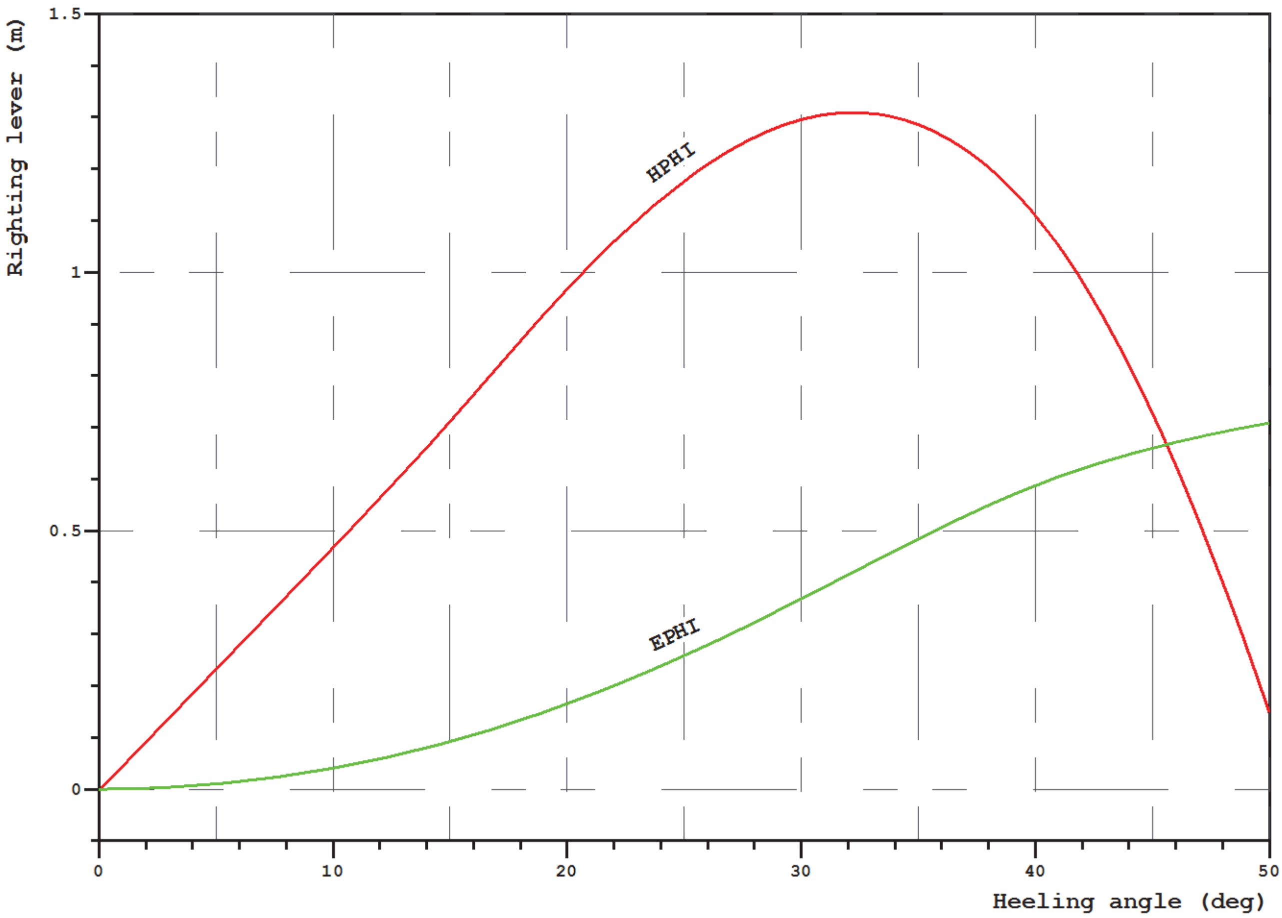
List of Loads

NAME	LOAD	MASS t	FILL %	XM m	YM m	ZM m	FRSM tm
CONTENTS=Black Water		(RHO=1)					
R110102	BLW	78.4	70.0	135.15	5.45	3.05	27.18
R110103	BLW	98.6	70.0	135.15	1.95	3.05	54.11
R110104	BLW	116.1	70.0	135.15	-2.30	3.05	88.21
R110105	BLW	60.9	70.0	135.15	-5.80	3.05	12.77
SUBTOTAL	BLW	354.0		135.15	0.00	3.05	182.27
CONTENTS=Diesel Oil		(RHO=0.86)					
R040504	DO	16.4	98.0	17.74	-13.35	16.01	0.00
R080102	DO	128.4	98.0	100.19	3.50	4.89	0.00
R080103	DO	128.4	98.0	100.19	-3.50	4.89	0.00
R100108	DO	121.4	98.0	126.70	0.00	3.52	0.00
SUBTOTAL	DO	394.6		104.92	-0.56	4.93	0.00
CONTENTS=Fresh Water		(RHO=1)					
R040102	FW	353.4	97.0	39.62	3.50	5.65	305.89
R040103	FW	353.4	97.0	39.62	-3.50	5.65	305.89
R160102	FW	331.6	80.0	213.70	4.19	4.87	775.33
R160103	FW	331.6	80.0	213.70	-4.19	4.87	775.33
R170102	FW	376.7	60.0	230.81	6.03	5.09	484.93
R170103	FW	829.2	60.0	232.71	0.00	3.81	1173.50
R170104	FW	376.7	60.0	230.81	-6.03	5.09	484.93
SUBTOTAL	FW	2952.7		181.73	0.00	4.81	4305.79
CONTENTS=Grey Water		(RHO=1)					
R050002	GW	321.2	80.0	56.74	4.88	1.45	1253.94
R050003	GW	321.2	80.0	56.74	-4.88	1.45	1253.94
R090002	GW	105.7	40.0	115.66	7.15	0.38	489.82
R090003	GW	126.9	40.0	115.66	0.00	0.38	846.41
R090004	GW	105.7	40.0	115.66	-7.15	0.38	489.82
R120002	GW	254.3	70.0	163.92	7.12	0.67	679.11
R120003	GW	307.8	70.0	164.06	0.00	0.67	1173.50
R120004	GW	254.3	70.0	163.92	-7.12	0.67	679.11
R140002	GW	332.9	80.0	191.57	4.25	0.87	1834.09
R140003	GW	332.9	80.0	191.57	-4.25	0.87	1834.09
R190001	GW	549.6	80.0	257.41	0.00	3.57	4413.00
R200001	GW	300.7	80.0	270.10	0.00	3.40	950.30
SUBTOTAL	GW	3313.2		168.92	0.00	1.56	15897.15

NAME	LOAD	MASS t	FILL %	XM m	YM m	ZM m	FRSM tm
CONTENTS=Heavy Fuel Oil (RHO=0.98)							
R090102	HFO	407.5	98.0	110.20	7.15	4.89	0.00
R090103	HFO	489.0	98.0	110.20	0.00	4.89	0.00
R090104	HFO	407.5	98.0	110.20	-7.15	4.89	0.00
R100102	HFO	106.6	98.0	118.39	8.70	4.89	0.00
R100103	HFO	97.2	98.0	118.39	5.45	4.89	0.00
R100104	HFO	92.2	98.0	117.96	1.95	4.37	0.00
R100105	HFO	84.2	98.0	118.05	-1.95	4.26	0.00
R100106	HFO	97.2	98.0	118.39	-5.45	4.89	0.00
R100107	HFO	106.6	98.0	118.39	-8.70	4.89	0.00
R120102	HFO	551.1	98.0	162.57	7.15	3.52	0.00
R120103	HFO	661.4	98.0	162.57	0.00	3.52	0.00
R120104	HFO	551.1	98.0	162.57	-7.15	3.52	0.00
SUBTOTAL	HFO	3651.6		136.78	0.00	4.20	0.00
CONTENTS=Heeling Water (RHO=1)							
R020002	HWB	589.0	100.0	11.38	15.82	11.06	0.00
R020003	HWB	589.0	100.0	11.38	-15.82	11.06	0.00
SUBTOTAL	HWB	1178.0		11.38	0.00	11.06	0.00
CONTENTS=Lubricating Oil (RHO=0.9)							
R060004	LO	11.4	80.0	70.11	2.90	2.54	3.51
R060005	LO	11.4	80.0	70.11	-2.90	2.54	3.51
R070002	LO	11.4	80.0	83.76	5.80	1.24	3.51
R070003	LO	11.4	80.0	83.76	0.00	1.24	3.51
R070004	LO	11.4	80.0	83.76	-5.80	1.24	3.51
SUBTOTAL	LO	57.2		78.30	0.00	1.76	17.55
CONTENTS=Miscellaneous (RHO=1)							
R060002	MIS	25.0	50.0	70.11	-6.17	0.80	4.96
R060003	MIS	26.6	50.0	70.11	6.31	0.80	5.93
R070005	MIS	16.6	50.0	84.14	-9.40	0.47	5.84
R070006	MIS	16.6	50.0	84.14	9.40	0.47	5.84
R080002	MIS	86.5	50.0	97.54	5.20	0.47	820.80
R080003	MIS	86.5	50.0	97.54	-5.20	0.47	820.80
SUBTOTAL	MIS	257.9		90.32	0.05	0.54	1664.18
CONTENTS= (RHO=1)							
(PERSONS)	PERSONS	560.0	0.0	130.00	0.00	30.00	0.00

NAME	LOAD	MASS t	FILL %	XM m	YM m	ZM m	FRSM tm
CONTENTS= (RHO=1)							
(POOLS)	POOLS	250.0	0.0	140.00	0.00	45.00	0.00
CONTENTS= (RHO=1)							
(STORES)	STORES	500.0	0.0	120.00	0.00	33.00	0.00
CONTENTS=Toilet (RHO=1)							
R100504	TOI	108.0	80.0	126.71	14.75	15.71	0.00
R100505	TOI	108.0	80.0	126.71	-14.75	15.71	0.00
SUBTOTAL	TOI	216.0		126.71	0.00	15.71	0.00
TOTAL		13685.3		140.40	-0.01	7.23	22066.94

Stability Curve



HEEL deg	MS m	HPHI m	EPHI mrad	FSMOM tm	DGZ m
0.0	-0.003	0.00	0.000	0.0	0.000
1.0	-0.004	0.04	0.000	385.2	0.005
5.0	-0.007	0.23	0.010	1897.9	0.027
10.0	-0.014	0.47	0.040	3322.9	0.047
15.0	-0.015	0.71	0.092	4256.3	0.060
20.0	-0.005	0.97	0.165	4845.9	0.069
30.0	-0.147	1.30	0.368	5548.2	0.079
40.0	-0.763	1.11	0.587	5840.3	0.083
50.0	-2.101	0.15	0.709	5785.4	0.082